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APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
09/923,470	08/06/2001	Edward J. Grenchus JR.	END920010061US1	1539

7590 10/04/2005

Shelley M Beckstrand, P.C.
Attorney at Law
314 Main Street
Owego, NY 13827

EXAMINER	
STIMPAK, JOHNNA	

ART UNIT	PAPER NUMBER
3623	

DATE MAILED: 10/04/2005

Please find below and/or attached an Office communication concerning this application or proceeding.

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PTO-90C (Rev. 10/03)

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Office Action Summary	Application No. 09/923,470	Applicant(s) GRENCHUS ET AL.	
	Examiner Johnna R. Stimpak	Art Unit 3623	

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --

Period for Reply

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE 3 MONTH(S) OR THIRTY (30) DAYS, WHICHEVER IS LONGER, FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133). Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

Status

1)☒ Responsive to communication(s) filed on *06 August 2001*.

2a)☐ This action is **FINAL**. 2b)☒ This action is non-final.

3)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

Disposition of Claims

4)☒ Claim(s) *1-32* is/are pending in the application.

4a) Of the above claim(s) _____ is/are withdrawn from consideration.

5)☐ Claim(s) _____ is/are allowed.

6)☒ Claim(s) *1-32* is/are rejected.

7)☐ Claim(s) _____ is/are objected to.

8)☐ Claim(s) _____ are subject to restriction and/or election requirement.

Application Papers

9)☐ The specification is objected to by the Examiner.

10)☒ The drawing(s) filed on *06 August 2001* is/are: a)☒ accepted or b)☐ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

Replacement drawing sheet(s) including the correction is required if the drawing(s) is objected to. See 37 CFR 1.121(d).

11)☐ The oath or declaration is objected to by the Examiner. Note the attached Office Action or form PTO-152.

Priority under 35 U.S.C. § 119

12)☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

a)☐ All b)☐ Some * c)☐ None of:

1.☐ Certified copies of the priority documents have been received.

2.☐ Certified copies of the priority documents have been received in Application No. _____.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

* See the attached detailed Office action for a list of the certified copies not received.

Attachment(s)

1) ☒ Notice of References Cited (PTO-892)
2) ☐ Notice of Draftsperson's Patent Drawing Review (PTO-948)
3) ☐ Information Disclosure Statement(s) (PTO-1449 or PTO/SB/08) Paper No(s)/Mail Date _____.
4) ☐ Interview Summary (PTO-413) Paper No(s)/Mail Date. _____ .
5) ☐ Notice of Informal Patent Application (PTO-152)
6) ☒ Other: *105 Requirement*.

M

DETAILED ACTION

1. The following is a first office action upon examination of application number 09/923,470. Claims 1-32 are pending and have been examined on the merits discussed below.

Claim Rejections - 35 USC §101

2. 35 U.S.C. 101 reads as follows:

> Whoever invents or discovers any new and useful process, machine, manufacture, or composition of matter, or any new and useful improvement thereof, may obtain a patent therefor, subject to the conditions and requires of this title.

3. Claims 1-32 are rejected under 35 U.S.C. 101 because the claimed invention is directed to non-statutory subject matter. For a claimed invention to be statutory, the claimed invention must produce a useful, concrete, and tangible result. In the present case, the invention is not concrete since the claimed complexity factor is not fully described so that one of ordinary skill in the art would know how to determine the complexity factor thereby leading to non-repeatable results in determining the complexity factor and staffing requirements. Since the invention is not concrete, the staffing requirements that are determined are not useful and are not tangible. Furthermore, in claim 5, the step of determining salvageable and disposable content is also not described in such a way that one skilled in the art would be able to make the determination. Specifically, there are no set guidelines for determining what characteristics make some material content salvageable and some material content disposable. As disclosed, the method of determining salvageable or disposable contents is completely subjective since depending on who is making the determination; the same part or item could be deemed as salvageable or disposable.

Since the recited process produces neither a useful, concrete, nor tangible result, claims 1-32 are deemed non-statutory subject matter.

In addition, claim 32 is mere program per se since there is no recitation of the program product being executable and no recitation of having instructions stored in a computer readable medium which is non-statutory.

Claim Rejections - 35 USC § 112

4. The following is a quotation of the first paragraph of 35 U.S.C. 112:

> The specification shall contain a written description of the invention, and of the manner and process of making and using it, in such full, clear, concise, and exact terms as to enable any person skilled in the art to which it pertains, or with which it is most nearly connected, to make and use the same and shall set forth the best mode contemplated by the inventor of carrying out his invention.

5. Claims 1-32 are rejected under 35 U.S.C. 112, first paragraph, as failing to comply with the enablement requirement. The claim(s) contains subject matter that was not described in the specification in such a way as to enable one skilled in the art to which it pertains, or with which it is most nearly connected, to make and/or use the invention. Specifically, the determination of the complexity factor is not described in such a way to enable one skilled in the art to make and/or use the invention. The only explanation of the complexity factor describes it as being determined by disassembly prototyping, which is completely subjective. The difficulty of disassembling material can be viewed differently depending on who or what is performing the disassembly. The complexity factor is subjective in that it is not fully described how one would disassemble or dismantle material and determine the complexity without some type of guidelines explaining what determines the level of complexity. Without fully understanding how to

determine the complexity factor, one would also not be enabled to determine the staffing requirements.

6. Furthermore, the step of determining salvageable and disposable content is also not described in such a way to enable one skilled in the art to make/and or use the invention. Specifically, there are no set guidelines for determining what material content should be salvaged and what material content should be disposed of. As disclosed, the method of determining salvageable or disposable contents is completely subjective since depending on who is making the determination; the same part or item could be deemed as salvageable or disposable.

7. The following is a quotation of the second paragraph of 35 U.S.C. 112:

> The specification shall conclude with one or more claims particularly pointing out and distinctly claiming the subject matter which the applicant regards as his invention.

8. Claims 1-32 are rejected under 35 U.S.C. 112, second paragraph, as being indefinite for failing to particularly point out and distinctly claim the subject matter which applicant regards as the invention. Specifically, the determination of the complexity factor is unclear since there it is not fully disclosed how one of ordinary skill in the art would disassemble material and determine a complexity factor without some type of guidelines explaining what determines the level of complexity. The only explanation of the complexity factor describes it as being determined by disassembly prototyping, which is completely subjective. The difficulty of disassembling material can be viewed differently depending on who or what is performing the disassembly.

9. Also, the step of determining salvageable and disposable content is also not described in such a way to enable one skilled in the art to make/and or use the invention. Specifically, there are no set guidelines for determining what material content should be salvaged and what material

content should be disposed of. As disclosed, the method of determining salvageable or disposable contents is completely subjective since depending on who is making the determination; the same part or item could be deemed as salvageable or disposable.

10. Claims 16-18 are rejected under 35 U.S.C. 112, second paragraph, as being incomplete for omitting essential elements, such omission amounting to a gap between the elements. See MPEP § 2172.01. Claims 16-18 recite no structural system elements. A system is treated as an apparatus as defined by its structural limitations, however, claims 16-18 recite no structural elements. For example, in claims 16 and 18, the claimed model is construed as a collection of data or formulas and, in claim 17 it is questionable what the structure of the database is. Clarification is required.

Conclusion

11. The prior art made of record and not relied upon is considered pertinent to applicant's disclosure.

Lee and Ishii. Demanufacturing Complexity Metrics in Design for Recyclability

Grenchus et al. Demanufacturing of Information Technology Equipment

Grenchus – Overview of IBM's Demanufacturing Process

Sandborn and Murphy– A Model for Optimizing the Assembly and Disassembly of Electronic Systems

Assembly/Disassembly Optimization Model (the "salvage" model).

McLees – Rapid Prototyping

Fields et al, US 5,111,391 – system and method for making staff schedules as a function of available resources as well as employee skill level, availability and priority

Yuri et al, US 6,249,715 – method and apparatus for optimizing work distribution

Gadh et al, US 6,725,184 – assembly and disassembly sequences of components in computerized multicomponent assembly models

Suzuki et al, US 6,226,617 – product disposal system

12. This Office action has an attached requirement for information under 37 C.F.R. § 1.105. A complete response to this Office action must include a complete response to the attached requirement for information. The time period for reply to the attached requirement coincides with the time period for reply to this Office action.

13. Any inquiry concerning this communication or earlier communications from the examiner should be directed to Johnna R. Stimpak whose telephone number is 571-272-6736. The examiner can normally be reached on M-F 8am-4:30pm.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Tariq Hafiz can be reached on 571-272-6729. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300.

Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair-direct.uspto.gov. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free).

JS
9/5/05

TARIQ R. HAFIZ
SUPERVISORY PATENT EXAMINER
TECHNOLOGY CENTER 3600

37 CFR § 1.105 - Requirement for Information

Applicant and the assignee of this application are required under 37 CFR 1.105 to provide the following information that the examiner has determined is reasonably necessary to the examination of this application.

The information is required to identify products and services embodying the disclosed subject matter of determining staffing requirements for a demanufacturing enterprise. Based on page 27 of the article "The Quest for Environmental and Productivity Improvements at the IBM Demanufacturing and Asset Recovery Center", by two named individuals on the present patent application, Edward Grenchus and Robert Keene, and also two additional individuals, Charles Nobs and Larry Yehle (submitted as prior art in application number 09/524,366), in 1996-1997 a disassembly line process was established to sequentially dismantle equipment, "teardown" analysis modeling was used to provide an analytical approach to disassembly, and staffing philosophy was modified for matching staffing required for specific dismantle teams.

Examiner requests any information about determining staffing requirements for a demanufacturing enterprise that was known and/or used at the time of submission of the present patent application. For example, the claims are directed to dismantling material and determining complexity factors for determining staffing requirements, whereas, the article discloses dismantling equipment and identifying skills for specific dismantling and matching staffing required for the dismantling. There appears to be a relationship between the claimed subject matter and the subject matter disclosed in the above-identified article.

The fee and certification requirements of 37 C.F.R. § 1.97 are waived for those documents submitted in reply to this requirement. This waiver extends only to those documents

within the scope of this requirement under 37 C.F.R. § 1.105 that are included in the applicant's first complete communication responding to this requirement. Any supplemental replies subsequent to the first communication responding to this requirement and any information disclosures beyond the scope of this requirement under 37 C.F.R. § 1.105 are subject to the fee and certification requirements of 37 C.F.R. § 1.97.

The applicant is reminded that the reply to this requirement must be made with candor and good faith under 37 CFR 1.56. Where the applicant does not have or cannot readily obtain an item of required information, a statement that the item is unknown or cannot be readily obtained will be accepted as a complete response to the requirement for that item.
This requirement is an attachment of the enclosed Office action. A complete response to the enclosed Office action must include a complete response to this requirement. The time period for reply to this requirement coincides with the time period for reply to the enclosed Office action, which is 3 months.

In response to this requirement, please provide the citation and a copy of each publication that any of the applicants authored or co-authored and which describe the disclosed subject matter of determining staffing requirements for a demanufacturing enterprise.

In response to this requirement, please provide the citation and copy of each publication that is a source used for the description of the prior art in the disclosure. For each publication, please provide a concise explanation of that publication's contribution to the description of the prior art.

In response to this requirement, please provide the citation and a copy of each publication that any of the applicants relied upon to develop the disclosed subject matter that describes the

applicant's invention, particularly as to developing staffing requirements for a demanufacturing enterprise. For each publication, please provide a concise explanation of the reliance placed on that publication in the development of the disclosed subject matter.

In response to this requirement, please provide the citation and a copy of each publication that any of the applicants relied upon to draft the claimed subject matter. For each publication, please provide a concise explanation of the reliance placed on that publication in distinguishing the claimed subject matter from the prior art.

In response to this requirement, please state the specific improvements of the claimed subject matter in claims 1-32 over the disclosed prior art and indicate the specific elements in the claimed subject matter that provide those improvements. For those claims expressed as means or steps plus function, please provide the specific page and line numbers within the disclosure that describe the claimed structure and acts.

In responding to those requirements that require copies of documents, where the document is a bound text or a single article over 50 pages, the requirement may be met by providing copies of those pages that provide the particular subject matter indicated in the requirement, or where such subject matter is not indicated, the subject matter found in applicant's disclosure.

JS
9/5/05

TARIQ R. HAFIZ
SUPERVISORY PATENT EXAMINER
TECHNOLOGY CENTER 3600

Notice of References Cited	Application/Control No. 09/923,470	Applicant(s)/Patent Under Reexamination GRENCHUS ET AL.	
	Examiner Johnna R. Stimpak	Art Unit 3623	Page 1 of 2

U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	Classification
	A	US-6,725,184	04-2004	Gadh et al.	703/2
	B	US-6,226,617	05-2001	Suzuki et al.	705/1
	C	US-6,249,715	06-2001	Yuri et al.	700/111
	D	US-5,111,391	05-1992	Fields et al.	705/9
	E	US-			
	F	US-			
	G	US-			
	H	US-			
	I	US-			
	J	US-			
	K	US-			
	L	US-			
	M	US-			

FOREIGN PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Country	Name	Classification
	N					
	O					
	P					
	Q					
	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	Grenchus, Ed, Robert Keene, Charles Nobs, Larry Yehle. The Quest for Environmental and Productivity Improvements at the IBM Demanufacturing and Asset Recovery Center. 2001 □□from PTO-1449 filed with 09/524,366
	V	Lee, Burton H. and Kosuke Ishii. Demanufacturing Complexity Metrics in Design for Recyclability. 1997 IEEE□□from PTO-1449 filed with 09/524,366
	W	Grenchus, Ed, Robert Keene, Charles Nobs. Demanufacturing of Information Technology Equipement. 1997 IEEE□□from PTO-1449 filed with 09/524,366
	X	Grenchus, Edward J. Overview of IBM's Demanufacturing Process. □□from PTO-1449 filed with 09/524,366

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

Notice of References Cited	Application/Control No. 09/923,470	Applicant(s)/Patent Under Reexamination GRENCHUS ET AL.	
	Examiner Johnna R. Stimpak	Art Unit 3623	Page 2 of 2

U.S. PATENT DOCUMENTS

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	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	Sandborn, Peter A. and Cynthia F. Murphy. A Model for Optimizing the Assembly and Disassembly of Electronic Systems. IEEE Transactions on Electronics Packaging Manufacturing, Vol. 22, No. 2, April 1999. from Internet
	V	Sandborn, Peter. Assembly/Disassembly Optimization Model (the "salvage" model). December 24, 1999. from Internet site www.glue.umd.edu/~sandborn/research/salvage.html
	W	McLees, Lea. Rapid Prototyping - Key to Speedy Manufacturing. August 5, 1997. from Internet site www.gtresearchnews.gatech.edu/reshor/rh-spr97/proto.htm
	X	

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

The Quest For Environmental and Productivity Improvements at the IBM® Demanufacturing and Asset Recovery Center

Ed Grenchus, Robert Keene, Charles Nobs, and Larry Yehle
IBM Endicott Asset Recovery Center, Endicott NY
Global Asset Recovery Services
IBM Corporation

Abstract: As the life cycle of computers continues to decrease due to new technology and improved processing performance, many companies are faced with an increasing volume of returned end of life equipment. Without making dynamic changes to meet the required capacity, companies could be confronted with the need for more people, space, and capital equipment, all costly investments. Therefore, the performance of demanufacturing operations becomes critical to not only ensuring proper environmental disposal options, but also improving process efficiency and minimizing expense.

This paper will look at how the Global Asset Recovery Services organization of IBM and its' Asset Recovery Center (ARC) in Endicott, NY have been able to focus on improving both environmental performance and demanufacturing productivity while meeting the challenge of processing increased returns and controlling labor, space, and capital expense. The paper will identify and discuss the key actions taken over the past six years that have led to a continuing environmental disposal improvement. The amount of material dispositioned to the landfill has decreased by over 75%. It will also highlight changes and enhancements that have been made to the process and demanufacturing line to realize greater than three times growth in productivity.

I. Introduction

A. Background

In today's ever increasing digital world where the need for continuous information seems to be required in every aspect of our lives, it is easy to see the sheer amount of electronic products being used. Laptop computers, cell phones, and hand held systems, are omnipresent. No longer is it only the business executive who is seen in the airport calling on a cell phone or working with a laptop, rather, even the youngest of children are somehow using these mobile instruments of information and connectivity. We demand and push technology not only for quicker, smaller, and lighter systems but also for ones that provide more function and capability. The consequence of this demand is that electronic products have an ever decreasing life cycle which in turn generates an ever increasing volume of product at end of life requiring some sort of disposal. No where is this more evident than in the computer industry. Numerous articles and studies indicate sub 36 month technology life cycles and cite 10's of millions of units already obsolete. [1][2][3] The studies also forewarn of a gigantic pending waste stream consisting of 100's of millions of systems pending obsolescence in the next few years.[4][5][6][7] When coupled with greater consumer awareness of environmental issues, the demand for product takeback, environmental disposal legislation, and improved integrated supply chains for businesses, companies and recyclers must be prepared to address the high amount of projected product returns both efficiently and in an environmentally sound manner.

This paper will discuss how IBM's Asset Recovery Center (ARC) in Endicott, NY of the Global Asset Recovery Services organization has been able to meet the challenge of processing increasing returns while improving both environmental performance and demanufacturing productivity. Throughout the paper, the reader must understand the criticality of having the support of an engineering infrastructure to identify and implement methods to achieve improvements. Without this support the productivity and landfill reduction improvements would not have been realized.

B. Operational Overview

In late 1994, IBM established an Asset Recovery Center (ARC) in Endicott, New York. The ARC operation was initially set up as a dismantle and impairment line used to guarantee asset protection and proper environmental disposal. In 1996, the line expanded it's capability to include parts recovery. This opportunity for parts harvesting generated additional sub-processes to support both internal and external parts reuse. Internally, the parts have been reused to supply IBM field service programs. These parts can be either tested or untested based on customer requirements. Externally, the parts and components are sold through an established broker network primarily in an "as is" condition. [8][9][10] The result is that through year end 2000, the ARC has processed over 220 million pounds of both IBM and OEM equipment, making it IBM's largest Recovery Center in the world. Figure 1 below depicts the annual amount of material processed in millions of pounds. The mix of input material has been comprised of approximately a 60/40 split of machines and parts. The yearly average is over 30 million pounds

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and the graph shows a three times growth in pounds processed since 1994.

ANNUAL POUNDS PROCESSED
ARC, Endicott, NY

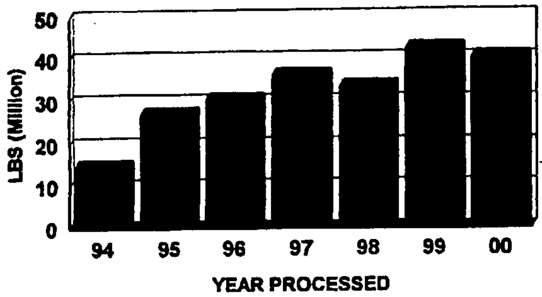

Figure 1

Figure 2 shows the high level flow of inputs and outputs of the Demanufacturing line.

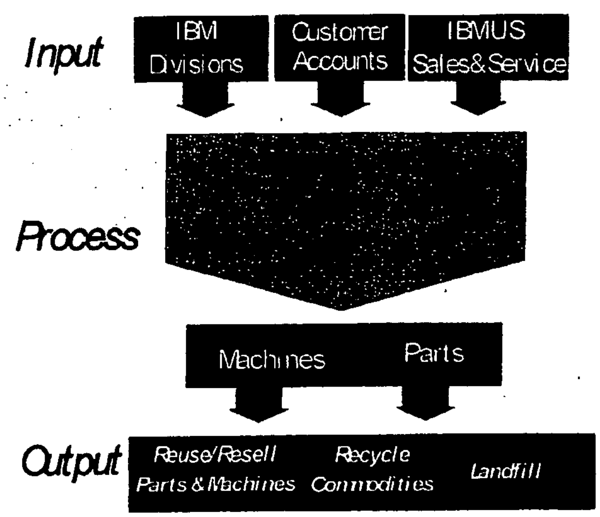

Figure 2

Additionally, in the first quarter of 1999, the ARC became part of the newly formed Global Asset Recovery Services (GARS) organization. This unit was established to provide IBM with a single world wide focus for managing the disposition of all IBM and non-IBM returned, surplus, and idle computer and hardware inventory.

Some key demanufacturing operational demographics are:

1. ISO 14001 certified
2. an annual demanufacturing processing capacity greater than 50 million pounds
3. approximately 500,000 square feet of secure processing space
4. linkage to an automated warehouse that can store up to 20,000 pallets of material at once

II. Productivity and Efficiency Improvements

As the volume of input grew, the ARC was challenged to increase its throughput while containing space and headcount, as best possible, in order to minimize expense. To do this, the unit went through a series of intensive Activity Based Costing sessions to identify, evaluate, and implement cost savings ideas. The results were extraordinary. As seen in Figure 3, productivity in pounds processed per person as measured from the 1994 base, has significantly increased as measured from 1994. This means that without improvement, the staffing would have had to almost triple in order to meet the 2000 demand.

PRODUCTIVITY
(As measured against 1994)

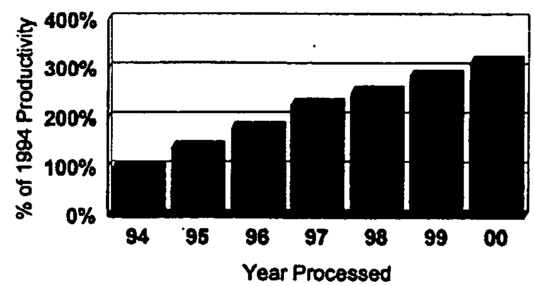

Figure 3

Below is a chronological listing and explanation of key individual improvements that contributed to the rise in productivity.

- <u>1994 -1995</u>
  - Pneumatic / Electric Disassembly Tools - the change from basic hand to power driven tools which allowed quicker disassembly times
  - Staging and grouping "like" items for disassembly - this minimized change over and set up times, tool changes and improved operator efficiency through repetition
- <u>1995 - 1996</u>
  - Installation of a pallet movement conveyor system - minimized the number of fork lift operators required to transport product to the dismantle area. The conveyor also allowed the floor technician to have more control to batch product thereby creating

longer disassembly runs

- Installation of a commodity sort station belt conveyor - allowed commodities to be moved to an area where sorting is conducted by trained experts. This decreased the amount of sort classification errors and virtually eliminated the need for resorts. It also allowed dismantle operators to focus solely on dismantle technique

- Automated commodity weigh scales - integrated weigh scales into the sort station belt conveyor operations and minimized handling associated with weighing output material

- Enlarged Shredder hopper - allowed for the use of a rotate and dump fork lift which minimized the support requirements at the shredder load station

- Implementation of workload planning model - allowed for a dynamic manpower planning tool which allowed management to react rapidly to workload changes.

- Implementation of External Parts Sales - reduced the number of machines and subassemblies sent to dismantle by screening and sorting out industry standard parts for potential external sale

- 1996 - 1997

  - Replacement of the vertical baler with higher thruput horizontal baler - increased baler thruput and minimized baler support requirements

  - Implementation of the Disassembly Line process - established "teams" to sequentially dismantle equipment in a reverse sequence process

  - Development and implementation of "Teardown" analysis modeling - provided a more analytical, rather than empirical, approach to disassembly. Standardized the steps, expected recovery, and dismantle end point on a machine by machine basis

  - Modified the overall staffing philosophy - identified specific skills and matched staffing required for specific dismantle teams

- 1997 - 1998

  - Dock to floor pallet movement capability - allowed product to be moved by conveyor to and from the receiving and shipping docks

  - Material prescreen and sort on the receiving dock - Screened out inappropriate material from being moved to the Dismantle area

  - Expanded External Sales for hard drives and monitors - minimized material disassembly by recovering these items as sellable units

  - Formalized Training and Certification of Operators - standardized the approach to operator training and established certification criteria

- 1998 - Present

  - Installation of an overhead gantry in Large Machine teardown - allowed for quicker disassembly of large machines by assisting operators with the movement of the machine from one disassembly station to the next

  - Module Pull card batching - allowed for the batching of similar cards prior to module pull operations thereby minimizing change over and set up times and improving efficiency through repetition

  - Consolidated the External Sales operations into a single area - reduced the movement of material to and from the sales areas

The result of the changes can be seen in figure 4. The graph indicates that the ARC needs even less people today than when it started in 1994 to process greater than 2.8 times the input volume.

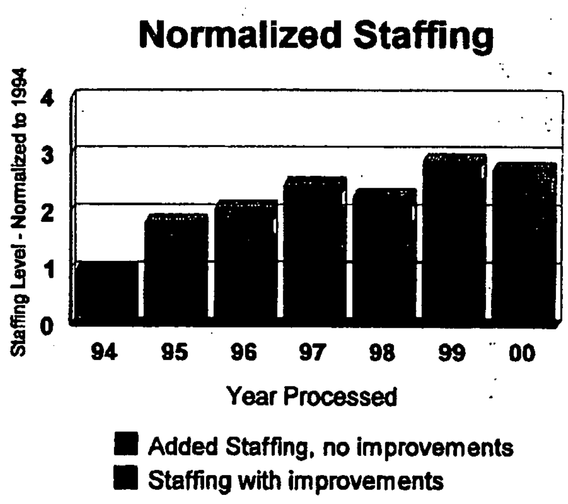

Figure 4

III. Environmental Performance and Improvements

Just as remarkable has been the continuous improvement in environmental performance as measured by the amount of material landfilled. Since the ARC is not a primary material recycler, the waste stream was addressed through two major efforts, finding reuse / resale opportunities for equipment and parts and finding recycling brokers for residual commodities. In this arena, existing regional recycling infrastructure usually dictates the outcome. The process is straightforward and simple. Search until you find a broker or recycler that needs or wants your material, minimize any consolidation and transport cost, and the waste stream gets reduced.

Figure 5 below shows the percent of material received that actually was shipped to the landfill for disposal. The slight increase from 1995 to 1996 was the result of losing the plastic recycling vendor, but the net result shows over a 75% reduction in the percentage of material processed sent to the landfill since 1994.

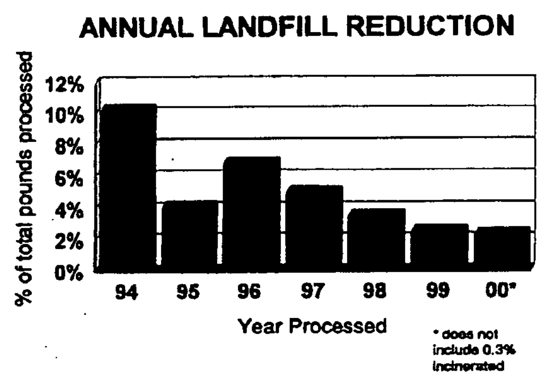

Figure 5

As a point of reference, ferrous and non-ferrous recylers were established at startup. To achieve these landfill reductions, the following key activities were implemented:

- Commodities
  - The basic activity here is to search, and search again, until a commodity vendor for each material is found. Once identified, the next steps are to work closely to with the vendor and negotiate material purity requirements and economic shipping / transportation quantities. The requirements are then set up in the disassembly and sort area.

  So far, the ARC has been able to find brokers and recyclers for:
  * Ferrous metals
  * Non-Ferrous metals
  * Precious metals
  * Wood
  * Styrofoam
  * Urethane
  * Paper
  * Lightly Contaminated Cardboard
  * Hard Plastics
  * Batteries
  * Monitors / CRT's

- Process
  - Activities here are:
    - Continuous screening of the input material with an outlook for sale or reuse opportunity
    - Improved commodity sort / commodity identification techniques
    - Improved shipping formats and a reusable container strategy

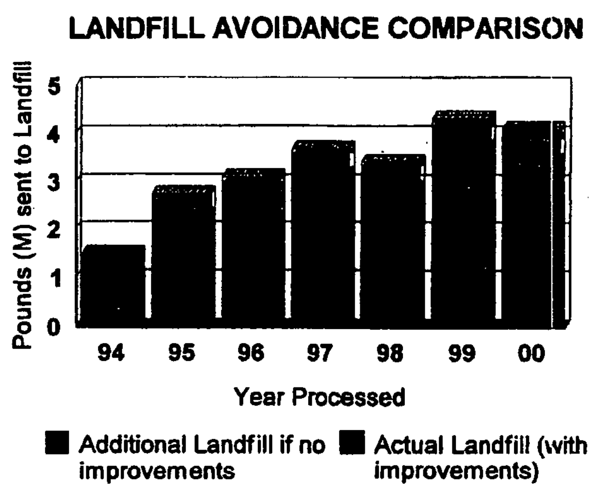

Figure 6

As seen in figure 6 above, the quantitative results from 1994 through 2000 indicate that with improvements to the waste stream, over 10 million pounds of additional material have been diverted from the landfill, if the landfill rate is normalized to the 1994 base. When one looks at the "entire" picture from 1994 through year end 2000, over 220 millions of pounds of incoming material has been recovered through either reuse, resale, and recycle action.

Some interesting facts are:

1. The amount of ferrous metal processed and recovered through recyclers is equivalent in weight to over 50% of the weight of the steel used in the frame of the Empire State Building.

2. If the amount of cardboard and paper that was recycled and baled into 3 ft x 4 ft x 5ft bales and laid end to end, the entity would span the Golden Gate Bridge over 7.7 times.

3. The amount of weight of the ferrous and non ferrous metals processed for recycling is equivalent to the weight of 133 fully loaded Boeing® 747 jets at take off.

4. If the weight of all hardware processed is extrapolated to a standard personal computer in weight and volume, the volume of PC's would roughly fill an acre of land piled 300 feet high.

IV. Summary

In summary, it can be seen that the Endicott Asset Recovery Center has systematically improved its performance both environmentally and operationally while significantly increasing throughput. The achievements are not the consequence of a singular activity or event. Rather, the improvements have evolved over time and are the result of continuous modifications to the process and waste stream.

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TRADEMARKS

DEMANUFACTURING COMPLEXITY METRICS IN DESIGN FOR RECYCLABILITY

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Abstract - This paper proposes a new design chart and associated recycling complexity metrics to aid in the early identification of product subassemblies with recyclability enhancement opportunities. The *recyclability map* combines sort complexity and scrap rate information available to the designer at an early stage in the design. The map helps designers optimize recyclability by highlighting subassemblies where appropriate material selection and disassembly redesigns can reduce scrap rate and retirement costs. Research contributions include development of the sort bin metric to model the impact of variable recycling process technologies in demanufacturing, and elaboration of the recyclability map approach. Redesign of an inkjet printer for improved recyclability is used as a validation example.

I. INTRODUCTION

The recent emphasis on design for environment (DFE; Allenby, 1993) urges designers to include environmental impact along with many other product requirements. Product take-back laws in Europe (Beitz, 1993) and the recyclability laws in Japan (Hattori and Inoue, 1992) demand a highly focused goal of design for recyclability. Selection of materials from their life-cycle perspective is a crucial factor influencing product recyclability (Ishii et al., 1994). Common to these approaches is the notion of concurrent planning for post-life use of the product in the early stages of design, i.e., design for product retirement (DFR; Ishii et al. 1992; Marks, et al. 1993). Implicit in these perspectives is also an assumption of a homogeneous, static and well-known recycling process environment. Many factors make effective advance planning for product retirement extremely difficult:

- advancing recycling process technologies
- country-to-country disparities in recycling processes
- great variability in retirement timing
- recycled materials commodity market fluctuations

Uncertain factors outside the control of the designer are not considered in DFR optimality.

This paper takes the viewpoint of demanufacturing plants or recycling organizations (Figure 1) which sustain a broad, system-wide view of product recycling process technologies and economics. From this perspective, the product recycling and retirement process appears highly uncertain and variable. Not only must the recycling organization consider the recyclability of entire product lines and families, they also frequently handle multiple generations of products from any stage of the supply chain (Ishii et al., 1995). In some cases, the recycling organization may have to process products from different manufacturers. Current DFE methods fall short in accounting for these and other external uncontrollable factors.

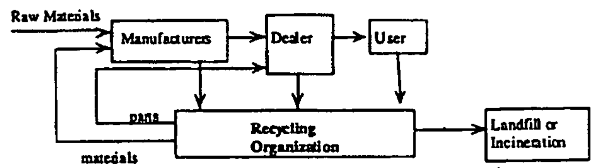

Figure 1. Design Method focusing on Demanufacturing Process

We propose a new framework that categorizes and describes the major recyclability factors in terms of product-independent and product-dependent complexity and uncertainty. The *recyclability map*, a chart indicating the recyclability of a particular product and its constituent modules under a given recycle process, provides a graphical method for performing robust DFR. The chart combines sort and disassembly complexity metrics, as well as material recovery efficiency (scrap rate), helping designers improve the overall recyclability by appropriate material selection and modularity. The map framework supports DFR under product-independent uncertainty, and is intended for application in the early design phase. We close with a case study of a Hewlett Packard inkjet printer which demonstrates concurrent use of the recyclability map and *reverse fishbone diagram* disassembly analysis methodologies (Ishii and Lee, 1996) to propose and verify recyclability design improvements of subassemblies.

II. DESIGN FOR RECYCLABILITY UNDER UNCERTAINTY

Design for Recyclability (DFR) under uncertainty requires designers to make the environmental friendliness of their product relatively independent of uncontrollable factors. Product-independent variables are those features of the product's end-of-life external environment that affect its recyclability. The level of recycling process technology and corporate parts reuse policies are examples of uncertainties common to many products. Controllable design factors are those which the designer can fully determine during the product design phase such as material selection and design configuration. Three important sources of DFR uncertainty are recycling process technologies, timing of product

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retirement, and the absence of design data. Other uncertain factors such as regulations and industrial standards can also significantly impact configuration and materials selection decisions.

A. Recycling Process and Technology Changes

The sophistication of recycling technology varies across geographic boundaries, between recycling organizations, and over time. A single product model can be subject to a range of recycling processes in multiple country markets. Our work has illustrated how the sophistication of available recycling technologies plays a significant role in the level of product disassembly and sorting (Table I). The degree to which a particular recycling process can handle different types of plastics dictates the level to which plastics must be separated for color, filler content, and other characteristics. Materials compatibility issues must be seen relative to the product-external context of available recycling technologies.

B. Timing of Product Retirement

Available literature on product retirement assumes that products are retired exclusively near the end of their useful life, when the customer upgrades or discards the item. However, our work reveals that the timing of product retirement is highly uncertain, because it can occur at any point in the product life cycle. One recent case study performed with Hewlett Packard indicated that several printer products are retired within weeks of their manufacture due to excess retail inventories, customer returns, and wholesaler overstocks returned directly to the manufacturer for disposal, reconditioning or spare parts extraction. Recycling facilities, therefore, increasingly perform full or partial disassembly of relatively new, unused products, together with disassembly of older used products at the end of their useful life. Thus, the timing of recycling operations can vary greatly for some products.

C. Design for Disassembly in the Absence of Data

Our recent work reveals concern and frustration over increasingly stringent design for recyclability requirements in the face of persistently large data gaps. These data gaps are pronounced in two areas: future process costs for disassembly and sorting, and materials data on compatibility, processing cost, demand and value.

Typically, when such data become available, it is too late in the design, often expensive and difficult to use. Because the disassembly process occurs in the future at many diverse locations, it can be difficult to design to known disassembly processes and costs. The absence of adequate data introduces a high level of uncertainty as to whether a particular design is optimal or sub-optimal from a recyclability perspective. Design for recyclability methods should ideally be able to generate useful metrics with minimal data collection and analysis under uncertainty.

D. The Disassembly Reverse Fishbone Diagram

To encourage design engineers to incorporate recyclability, we have defined the reverse fishbone diagram as a graphical representation of the product disassembly process (Ishii and Lee, 1996). The size and shape of the reverse fishbone tree indicate the complexity and cost associated with the demanufacturing process. Construction of the diagram forces designers to "walk through" the demanufacturing steps and aim for an efficient recycling process. While the reverse fishbone diagram proved effective for improving the recycle modularity of one product model, it falls short of helping designers generate effective recyclability ideas in material selection and assembly designs for product families and generations.

III. DEMANUFACTURING COMPLEXITY METRICS

A. Sort Complexity

Sort Complexity (SC) captures information about the difficulty and cost of the disassembly process as influenced by the following design-independent, product-external factors:

- Level of Recycling Technology Employed
- Level of Product Reuse/Re-manufacture

The sort complexity strongly influences the level of disassembly required when recycling or reusing a product. High sort complexity entails greater disassembly costs and therefore the designer must pay greater attention to disassembly and materials complexity. Thus, the concept of sort complexity captures several important characteristics of the corporate recycling process and can assist the firm in planning product DFE in context of the larger recycling technology and corporate parts reuse policy.

TABLE I: TECHNOLOGY LEVELS OF RECYCLING PROCESSES

Level	Characteristics	Process Description	Disassembly and Sorting
1	Unsophisticated recycling	Each part is sorted into its own bin, regardless of material content	Maximum disassembly and sorting required High cost retirement process
2	Function-based recycling	Combine similar parts into the same sort bin, based on part function	Intermediate disassembly and sorting
3	Material-based recycling	Each material is sorted into its own sort bin, regardless of part function	Intermediate disassembly and sorting
4	Material family recycling	Combine some different materials into the same sort bins	Minimum disassembly and sorting required
5	Advanced recycling technology	Combine all materials into one sort bin	No disassembly, sorting; Lowest cost process

Our principal sort complexity metric is "number of sort bins," where the sort bins are defined as any distinct end fate or destination for a product, module, subassembly or component. Examples of different sort bins include *scrap, ABS, steel,* and *motors.* Advantages of the sort bin metric are that it is easy to understand and readily estimated by the recycling organization. When considered in the context of the reverse fishbone diagram, the number of sort bins corresponds to the number of total different destinations for all the leaves on the diagram. In general, more sort bins indicate deeper levels of disassembly, higher material count, and low commonality. A good design for recycle modularity should lead to fewer sort bins for a given level of recycling process technology employed.

We assume that a particular product can be sorted into one to many sort bins. A highly sophisticated recycling technology ("Process Level 5", Table I) should be able to "sort" the product into only one bin, since the recycling process is capable of taking in multiple materials and separating them. On the other hand, sending the entire product to scrap constitutes a single sort bin. We assume that the "scrap" bin is least desirable among all possible sort bins because it is environmentally most harmful (requiring landfill or incineration). When particular materials require costly handling, such as toxic or radioactive materials, those sort bins should receive negative weightings or cost penalties. Other "usual" sort bins are ranked approximately equivalently.

The sort complexity (SC) is a function of disassembly (separation) and "clump" processing, for which the following section proposes metrics.

B. Materials Complexity

Materials complexity (MC) is determined during the design phase and plays an important role in determining disassembly decisions and total recycling cost. Materials complexity is relevant to the extent that the recycling technology is constrained in its ability to process all materials together.

Essentially, materials complexity refers to the number of materials utilized in a component, subassembly, or product. Depending on the particular context, it may be necessary to make the following additional distinctions:

- **Number of Material Classes:** Broadly, we can group materials into the following categories: plastics, ferrous and non-ferrous metals, paper and wood, hazardous materials, other. The number of different material classes strongly influences the materials complexity of components and assemblies.
- **Materials Compatibility:** Some combinations of materials may not be processed together during recycling. This is a strong function of the current level of recycling technology, as mentioned before.
- **Materials Requiring Special Handling:** Materials difficult and/or very costly to handle.

For simplicity, we assume here that all materials are broadly equivalent in "goodness" or "badness" ranking from an environmental perspective. The materials complexity metric does not reward or penalize particular material classes, or materials, selected by the designer.

C. Disassembly Complexity

While material complexity focuses on the processing cost of "clumps" after separation, disassembly complexity (DC) addresses the cost of disassembly and separation of the product into these "clumps." Obviously, the total disassembly cost is heavily related to the number of sort bins. However, DC is also dependent on the product design and the disassembly technology employed. Designers should provide for easy disassembly of each "clump" depending on its fate. Re-use clumps require easy non-destructive disassembly, whereas clumps to be ground allow for destruction of fasteners and the clumps themselves.

IV. THE RECYCLABILITY MAP

A. Recyclability Map Fundamentals

The recyclability map is a design chart for the early identification of modularity and disassembly strategies leading to significant reductions in recycling costs. The map can be used both as a global system-level tool to monitor and compare recyclability improvements across product families and generations, and also as a subsystem-level guide to component-specific redesigns for an individual product. The map is a companion tool of the reverse fishbone diagram in promoting a robust approach to advance planning of the disassembly and sorting process under uncertainty. It is most useful during the layout design phase, when alternate materials and configurations are under consideration. The map also supports tracking of DFR redesigns for subassemblies performed over the history of a product platform.

The recyclability map derives its analytical power from the unique use of simple sort and disassembly complexity ratings and material recovery efficiencies. Combining these metrics into an intuitive graphical representation facilitates quick trade-off analysis for design improvements at the subassembly and major component level, without placing heavy burdens on the designer for extensive data analysis. Sort bin count models the effect of alternative recycling technologies and processes, allowing designers to roughly compare a single design under alternative recycling process technology assumptions.

B. Information Required to Construct the Map

Construction of the recyclability map (Figure 2) requires layout design information and recyclability assessments by designers and recycling experts. First, the "fate" of major subassemblies and components must be identified. This step requires prioritization of product maintenance, parts reuse, recycling and regulatory compliance goals by designers and other involved parties. Analysis of product service and tear-down reports is one method of assessing part fates using historical data for a product family.

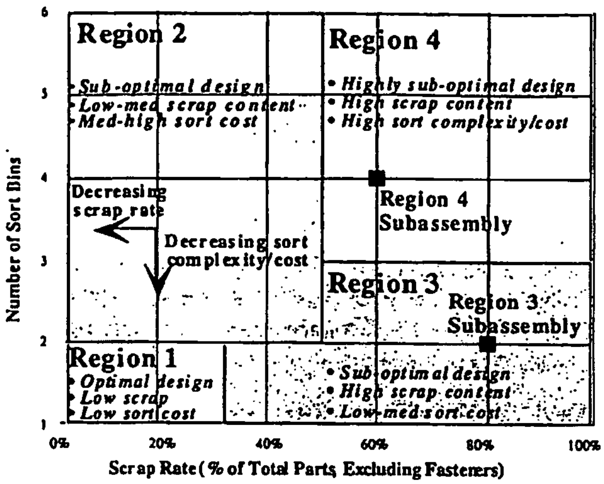

Figure 2: Recyclability Map Regions

Next, one estimates scrap rates for each module based on the percentage of total parts sent to scrap, i.e. to landfill. A low scrap rate is preferable, indicating a high degree of materials recovered from the module. In our work, we have assigned equal weighting to all parts in a module by using part counts; simple fasteners are excluded from part counts as they can improperly bias the metric.

The recycling organization assesses the sort complexity of a proposed design (Y-axis data), based on preliminary materials content and configuration choices made by the design team. For each module, major component or subassembly, the recycling organization identifies the total number of sort bins required after tear-down, removal, and disassembly. A high sort bin count is less desirable because of the increased cost of disassembly and sorting required. Thus, sort bin count serves as a proxy metric for disassembly and sort cost. The sort bin count may vary significantly, depending on the recycling process technology and regulatory environment assumed.

Successful use of the recyclability map necessitates early communication between the designer and recycling organization. An understanding of the disassembly and sorting process, as well as the range of possible recycling process technologies which are likely to be employed, is essential.

C. Construction of the Recyclability Map

Knowing the intended fate of each part, the designer generates the recyclability map for the complete, integral product, including all subassemblies where data is sufficient to permit useful qualitative analysis. For each subassembly, its position is plotted against the map X- and Y-axes, keeping in mind the level of uncertainty in the supporting scrap rate and sort complexity data.

If the current design is an iteration or version within a product family or generation, the designer may estimate X-Y coordinates on the current map starting with existing recyclability maps for related products using similar modules. As the design progresses, the map should be updated to reflect design tradeoffs and subassembly redesigns performed. Once directions for improvements to a particular subassembly have been set, the reverse fishbone diagram can help designers to quantitatively verify reductions in disassembly times and sort bin count. Design improvements may shift the subassembly to a new location on the map. Thus, the designer can iterate back and forth between the reverse fishbone and the map.

D. Analysis and Interpretation of the Recyclability Map

Qualitative analysis and interpretation of the recyclability map requires an understanding of how the map *regions*, subassembly *redesign paths* and *redesign costs* relate to the available design alternatives. Given a fixed recycling technology environment, the initial location of a subassembly on the map suggests directions for possible design improvements in material choice and disassembly strategy. Design improvements will move subassemblies from one region to another along one or more trajectories. Depending on the circumstances, movement along different trajectories between regions results from reducing or increasing material, disassembly, and/or sort complexity.

Region 1, characterized by low scrap rate and low disassembly/sort cost, is optimal for all subassemblies. Ideally, all subassemblies should fall in - or move towards - this region. Under ideal recycling technology and design, the product does not need to be disassembled and sorted at all, such that only one or two sort bins are required, with full material recovery. In practice, however, Region 1 is difficult and costly to attain.

Region 4 is highly undesirable for all subassemblies. Subassemblies of this type have a high scrap rate and high disassembly and sorting costs. Improvements can be made to Region 4 subassemblies by either reducing the scrap rate (moving to the left, towards Region 2), reducing the sort bin count (moving down towards Region 3), or by doing both (moving diagonally towards Region 1). Moving a subassembly towards Region 2 is essentially a materials selection decision; moving down towards Region 3 implies easier disassembly, a reduction in the number of materials, or changing to a more sophisticated recycling technology.

Most product subassemblies typically fall into Region 2 or Region 3. Region 2 subassemblies, already have low scrap rates and high recovery of material. The recyclability of these subassemblies can be improved through further increases in the recovery rate (move to the left) and/or reduction in sort complexity and cost (move down). Region 3 is where many subassemblies begin. Subassemblies in this region are characterized by low material recovery rates and low sort complexity and cost. Ideally, Region 3 subassemblies should seek to move directly towards Region 1; in practice, however, they will typically move first towards Region 2, since the available recycling processes are not sophisticated enough.

As a rule, the designer should initially target design improvements on subassemblies in Regions 3 and 4. Gains to be made from design improvements to these subassemblies are likely to be substantial compared to Region 2 subassemblies.

V. APPLICATION EXAMPLE

A. *Analysis of the HP Inkjet Printer 855C*

Inkjet printers produced by Hewlett Packard (HP) provided an appropriate case study to propel our development of the recyclability map concept. HP manufactures over 10 different models of the printer, and the models turn over regularly at approximately two year intervals. The printer uses many different materials ranging from commodity thermoplastics to expensive special purpose metal alloys. HP has a product retirement facility in Northern California, the Hardware Recycling Organization, that disassembles, sorts and recycles all printer models, including older generations, and with whom we worked closely during the validation phase of our research.

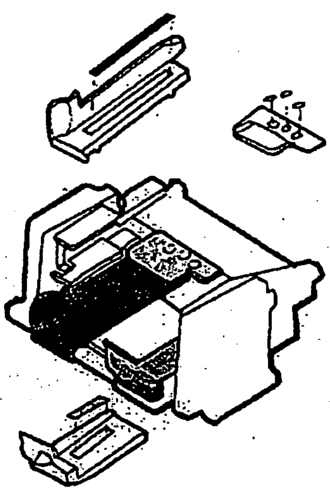

Figure 4: Printer I/O Paper Tray

A graduate student team in Stanford's ME217 Design for Manufacturability course developed the recyclability map to redesign the printer paper (I/O) tray and ink spittoon for a Hewlett Packard 855C Deskjet Printer (Figure 4). Figure 5 shows a chart that plots the number of sort bins against percentage of parts or materials that go to landfills or the incineration process (scrap). The example revealed two classes of "clumps" or subassemblies. The class on the bottom right (Group B assemblies, Region 3) consisted mainly of parts to be scrapped. Designers must consider different materials or modularity to enhance the reuse and recyclability. The paper tray, on the upper left (Group A assemblies in Region 2), had a high recovery rate in its original design. Here, the redesign goal is to reduce sort bin count and improve material recovery through appropriate material selection.

For the I/O tray, the map points to possible redesign improvements through reductions in scrap rate and sort complexity (see Figure 6). The team reduced the number of plastic materials from three to one (all ABS), and improved the disassembly process by changing fastening methods. The result is a reduction in the number of sort bins from four to three, a 70% decrease in disassembly time, and a 50% reduction of scrap (from nearly 35% to less than 15%), based on part count.

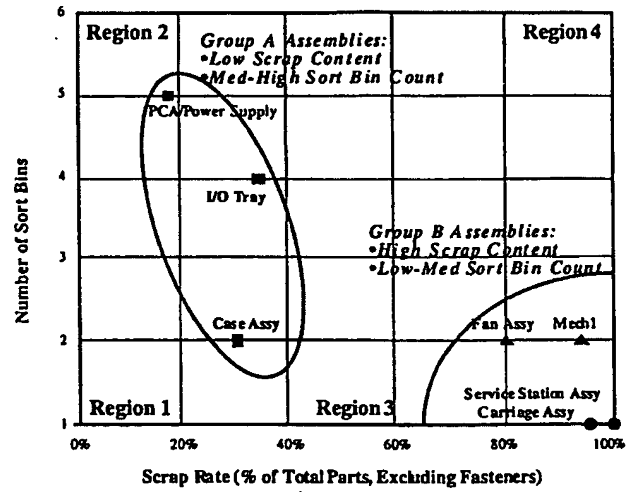

Figure 5. Recyclability Map for the HP 855C Printer

At an early point in the project, and with relatively little data on hand, the chart successfully identified areas of improvement and generated specific materials selection ideas. The student team had difficulty generating these ideas from the reverse fishbone diagram alone. The cooperation of the HP Hardware Recycling Organization was essential to this effort, and illustrated the benefits of early communication between the design team and recycling experts.

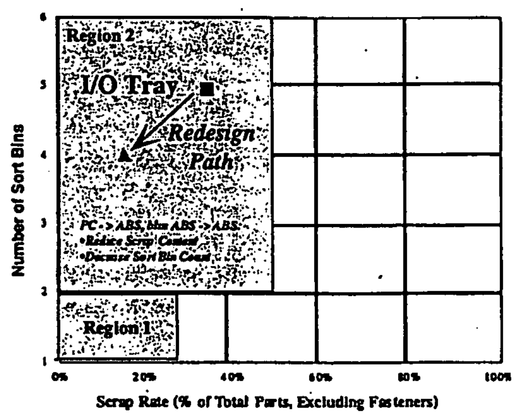

Figure 6: Redesign Path for Printer Paper Tray

B. *Limitations of the Recyclability Map*

The utility of the recyclability map depends on the data available to the designers, and the extent of analysis required. Successful use of the map depends on prior knowledge of the fate of all parts for each subassembly analyzed. Understanding the current and projected market demand for parts reuse and recycling is essential. In the worst case, the designer should consider all reusable parts as candidates for removal.

In its current form, the recyclability map assumes equal weightings are assigned to all sort bins, parts and functional modules. This has the advantage of simplicity, but may introduce distortions into the model that could be corrected through differential weightings. Our current sort complexity approach explicitly assumes that most sort bins are approximately equally desirable, i.e., we do not ascribe formal penalties or weightings to particular bin classes. Where particular materials require special, costly handling, such as toxic or radioactive materials, those sort bins should probably receive cost or environmental penalty weights, while other "normal" sort bins can be ranked equivalently.

We have also assigned equal weighting to all parts in a module by using part counts; thus a spring and plastic housing are considered equivalent in this scheme. Weightings by mass, volume and/or material type/class might prove more accurate. Simple fasteners are excluded (i.e. weighting = 0) from part counts, as they can bias certain classes of subassemblies towards the left side of the map, depending on the type of fastener material employed. Functional modules are equally weighted as well; electro-mechanical assemblies and static load-bearing structures such as housings are counted equivalently. This may make comparisons between subassemblies more difficult.

VI. CONCLUSIONS

This paper introduced the recyclability map as a new graphical design tool for the early identification of product subassemblies where appropriate material selection and disassembly redesigns can increase material recovery efficiency and reduce retirement costs. We began with a description of demanufacturing complexity metrics useful in representing uncertainty in external, uncontrollable design factors. The paper then described the recyclability map, and how it is used together with the reverse fishbone to perform DFR tradeoff evaluations. The HP inkjet printer study illustrated the practical application of the recyclability map.

The map can be used as a system-level tool to monitor and compare recyclability improvements across the full product design, and as a subsystem-level guide to component-specific redesign changes. It facilitates cross-generation and model-to-model comparisons within product families, providing a common basis for planning of incremental product redesigns aimed at improved recyclability over time.

While still in its infancy of development, early feedback from industry indicates that the use of recyclability map is effective in the following DFR tasks:

- Early identification of design for recyclability improvements at the subassembly level
- Advance planning and tracking of DFR improvements in product families over several generations
- Design for recyclability under uncertainty
- Assessment of product designs under alternative recycling process technology environments

The utility of the recyclability map is its construction and use as trade-off analysis and design review tool. It provides an additional motivation to bring together recycling organizations, designers and other parties responsible for the environmental impact of a product. The diagram can be employed as the basis for a collaborative design review and communication tool between manufacturing divisions and recycling organizations.

ACKNOWLEDGMENTS

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Demanufacturing of Information Technology Equipment

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Abstract-Efficient demanufacturing operations, with environmentally friendly and safe disposal streams, are being developed and installed to process obsolete and scrap computer and information technology equipment. IBM has designated the Endicott, New York facility as the prime Reutilization Center for IBM owned computer equipment in the United States. This paper will give a brief history and overview of the Endicott demanufacturing process, its capabilities, and waste management. Additionally, some challenges, methods, and solutions for processing and handling waste will be highlighted.

I. Introduction

In 1994, IBM established a Reutilization and demanufacturing line for IBM owned information technology equipment at its' Endicott, New York facility. The objectives of the line were to provide asset protection, insure proper environmental disposal of any residual material after dismantle, and maximize recovery to IBM. Recovery was to be achieved through reuse of machines and parts for IBM field service programs, by reselling recovered parts and material, and by recycling commodities by material content.

To date, the Reutilization line has processed over 70 million pounds of equipment and parts. It has saved IBM over $50 million through machine and parts reuse. Additionally, over $10 million has been recovered by selling industry standard parts and over $5 million through recycled commodities. The demanufacturing line encompasses over 200,000 sq. feet of process and storage space. It is staffed on 2 shifts and has an annual capacity of approximately 40 million pounds based on product mix and machine complexity. The operation is supported by a distinct engineering department that provides customer, process, material, recovery, and technical support for all aspects of reuse, reclamation, and recycling. It works closely with IBM's Engineering Center for Environmentally Conscious Products (ECECP) in Raleigh, North Carolina to feed forward disassembly techniques, advances, problems, or concerns for future product design improvements.

II. The Process

Endicott's process consists of 6 basic steps (see Figure 1). They are:

- Customer shipment
- Receipt acknowledgment / Inventory verification
- Staging
- Disassembly / Parts Reuse
- Commodity sorting / grading Shipment to Vendor(s) for recovery

The operations are linked using an internal tracking system

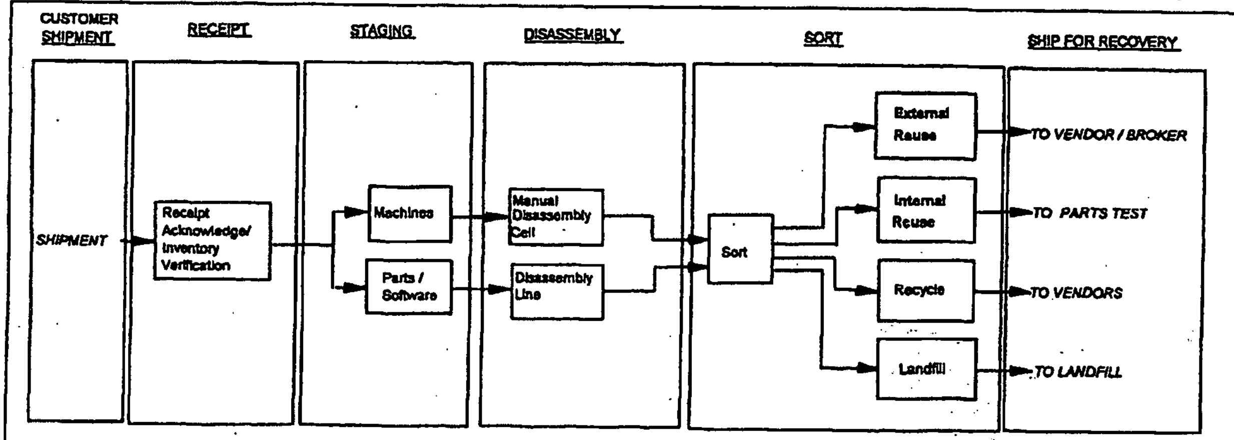

FIGURE 1. The Reutilization Process Flow

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(Reutilization Material Tracking System - RMTS) which maintains control and accountability of material being processed. Bar coding is used to insure data integrity.

III. Customer Shipment

The first step of the process involves initial contact with the customer to obtain an outlook for the incoming material. At this time, an estimate of amount, type, and timing of the shipment is determined. The sub-process ends with the generation of an Advanced Ship Notice.

In the past, typical problems with shipments have been encountered. They range from:

- Inability to identify who sent the truckload of material
- Poorly packed; loaded trailers
- Unexpected truck arrivals

Unlayering disclosed that customers are not always able to give definitive information about shipments (i.e. Truck bill, ship date, trucking company). A method needed to be developed to insure the ability to track shipments. The solution, was the assignment of a unique tracking numbers to each shipment. The numbers allowed identification of the shipment without knowing the specific truck bill number. As a result, control of incoming shipments has been significantly improved.

In order to avoid basic problems, the following guidelines for shipment have been established:

- Advance notification should clearly state the sender, location sent from, the shipper, and the inventory identifiers
- Uniquely identify the shipment
- Mark and number items in the shipment for easy inventory (inventory identifiers)
- Mark pallets / machines identifying sender.

IV. Receipt

The receipt process starts when the customer completes and sends the *Advanced Ship Notice*. It is designed to provide specific information about the shipment (the who, what, how, and when of the load). This information is also the first data entered into the automated tracking system so that when materials are unloaded from the truck, the truck contents can be inventoried by part number and serial number against the advance ship notice. If there are discrepancies, the customer is contacted for resolution. To close the loop, a "Receipt acknowledgment" note is sent back to the customer when the shipment has been satisfactorily verified. Movement of material to the staging area completes the receipt process.

V. Staging

For small machines, Personal Computers and desktop equipment, staging consists of segregating "like" material or machines in a holding area that area has been linked to the disassembly area via an intelligent conveyor system. This system allows the disassembly operation longer runs of similar equipment into the area. The result maximizes productivity through repetitive operations and less frequent lot changes. The system moves 90% of the material to the disassembly area. Items which can not be placed on the conveyor are trucked to an area where they can be floor staged. Significant savings in internal trucking expense has been realized due to this automated material handling system.

For medium and large machines, staging still consists of segregating large machines by type and model. All machines are trucked to the disassembly area by fork lift. In both cases, movement of material to the disassembly areas completes the staging process.

VI. Disassembly / Part Reuse

Disassembly is the center of the Reutilization process. At the macro level, this operation breaks down electronic equipment to prescribed reuse, recycle, or scrap levels. The objectives of the area are to:

- Obtain a high return from the sale of machines and parts (reuse)
- Achieve the optimum balance between commodity separation and separation expense
- Maximize the amount of material being reused or recycled.

and

- Render IBM products unusable (impairment)

The disassembly process is initiated after the material "pulled" from the staging area arrives in the work cell. Material ranges from:

- Raw materials
- Packaged software
- Boxed parts
- Desktop computer systems

to

- Large multi-cubical machines.

Due to different product complexity, items are routed to one of two areas for dismantle; the *manual disassembly cell* or a *disassembly line*.

A. Manual Disassembly Cell

The manual cell is designed primarily for disassembly of medium and large machines and material requiring unique handling. The layout of the cell allows flexibility in setup and 360 degree access to the work (See Figure 2). A typical cell is bordered on one side by a work bench. The other three sides are bordered by pre selected commodity containers. Filled commodity containers are moved to a weigh station where their weights are entered into the internal tracking system.

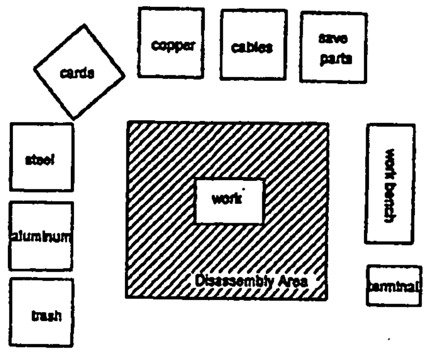

Figure 2. Layout of a Manual work station

B. Disassembly line:

The Disassembly line is designed for small machines (desk top PC's laptops, etc.), subassemblies / parts or any other material suitable for quick sorting.

The disassembly line consists of several long work benches (stations) adjacent to a belt conveyor (See Figure 3). A "reverse assembly line" method is used to disassemble or sort the product. Commodities are thrown onto the belt conveyor and moved to a sort loop area.

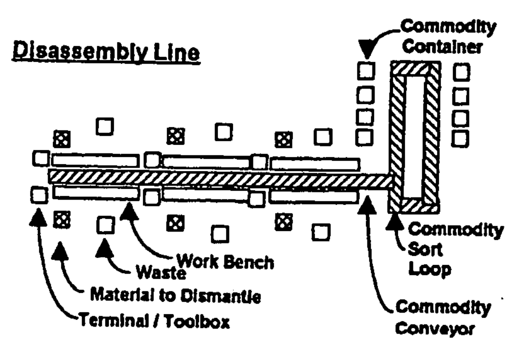

FIGURE 3. Disassembly Line Process Layout

VII. Commodity Sorting / Grading

The sort and grade operation segregates the disassembled materials into the proper commodities. Because of the two methods of disassembly (Manual Cell vs. Disassembly Line), two approaches to commodity sorting and grading are used.

A. Manual Cell - Sorting / Grading:

In the Manual Cell, commodities are sorted and graded by the disassembler. Commodity boxes are weighed and information about commodity type, grading, and weight is entered into the tracking system.

B. Disassembly Line - Sorting / Grading:

In the Disassembly line, commodities are moved to a loop where they circulate prior to grading (See Figure 3). Trained sorters remove and grade commodities and place them in the appropriate Commodity Container.

Greater accuracy in sorting has been achieved by placing "expert" sorters on a conveyor commodity loop. This process compromises some of the flexibility offered by the manual cell but improves recoveries and reduces identification errors.

VIII. Shipment to Vendor(s) / Customers for recovery

The final stage of the disassembly process is shipment to the appropriate vendor or customer for reuse, recycling, or landfill, with landfill being the least desired option. To date less than 10% of incoming material goes to landfill for disposal. See Figure 4.

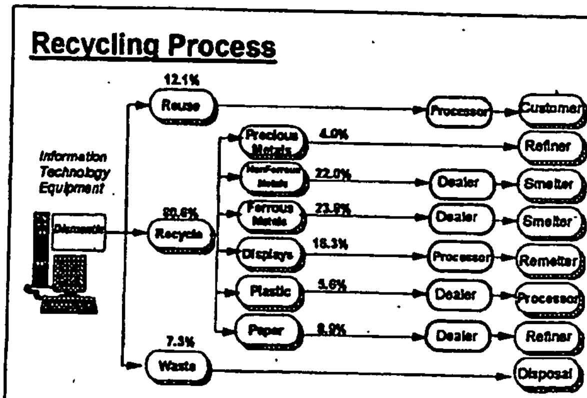

FIGURE 4. Recycling Process Streams

IX. Challenges and Actions

The result of proper cell layout for large machines and the conveyorized disassembly line for Personal Computers has allowed productivity to improve 35% over the past year. Even with this significant improvement, the disassembly and recovery process is not without its challenges. Aside from the daily changes in product mix, new personnel, and fluctuating commodity prices, some common issues are:

Product

- Batteries (type and location)
- Fasteners (multiple types, hidden, rivets)
- Part number identification and commonality
- Commodity (identification and grade)
- Adhesives & labels

Material

- Software packaging hierarchy
- paper identification (plasticized, coated, cardboard)
- Packaging material (shrink wrap, bubble wrap, Styrofoam)
- Paper binding (glue, spiral, ring binder)

Other

- Incoming packaging (mixed content, containers, pallets)
- Order of disassembly (standardization)
- Level of tear down for optimal recovery.

Activities are underway to address many of these challenges. Some specific actions are:

A. Design for the Environment (DFE):

Endicott is closely linked with the ECECP to feed forward problems, concerns, and improvements to development and designers for consideration in future products. Periodic workshops prioritize activities and insure face to face discussion and "hands on" hardware investigation.

B. Machine Analysis:

Complete machine type analysis for tear down, commodity recovery, and part reuse is routinely examined by engineering. A designated team of engineers and technicians tear apart and classify contents to maximize reuse and recovery of incoming machines and commodities.

C. Certified Spare Parts:

A process to recover parts for reuse in the field has been established. Parts are removed, tested, and restocked thereby reducing the need for new parts.

D. Other - Other activities underway are:

- Identification, classification, and categorization of computer plastics for improved recovery.
- Recommendations on software packaging hierarchy.

and

- Training and certification for computer disassembly to insure standardized practices for operators.

X. Summary

The IBM Endicott Reutilization Center continues to focus on asset protection and proper environmental disposal. Additionally, it maximizes recovery on used I/T equipment and parts. Actions and activities have been initiated for continuous improvement in its' disassembly operations. Endicott's "feed forward" information to designers on disassembly will assist IBM in addressing environmental concerns with used equipment in the future.

Overview of IBM's Demanufacturing Process

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Abstract

The IBM Asset Recovery Center is located in Endicott, New York. It was established in 1994 to demanufacture obsolete, excess, scrap computers, associated peripherals and parts. Dispositioning the material in an environmentally correct and safe manner while protecting IBM assets were key objectives. This paper gives a brief overview of the demanufacturing process used at the Asset Recovery Center.

Introduction

The IBM Asset Recovery Center in Endicott, New York was established in 1994 to dispose of IBM assets in an environmentally correct and safe manner. Parts, machines, and software are received from not only IBM internal locations, but also from field support units, branch offices, and external customers. As almost all material has some residual value, asset protection is stressed and maintained throughout the operation.

Some operational specifics on the Recovery Center itself are:

1. Greater than 200,000 square feet of process and storage area
2. Staffed on 2 shifts for an approximate 40 million pound annual capacity (dependent on product mix and machine complexity)
3. Closely linked with the IBM Used Part Return operation

Results to date on some of the operational metrics are:

1. Greater than 90 million pounds of equipment and parts processed
2. Greater than $11 million recovered through parts resale
3. Greater than $6 million saved by commodity recycling and recovery

Additionally, the operation has a dedicated engineering department that not only provides operational and process support and direction, but also links into IBM's Engineering Center for Environmentally Conscious Products for future product designs. Data is routinely shared between the Recovery Center and the Engineering Center on disassembly issues and concerns, recyclability, and Design for the Environment (DFE) attributes [1].

Dispositioning for demanufacturing at the Center generally follows the hierarchy shown in figure 1 where the greatest recovery value is through reuse and the least recovery value (cost) is material disposal.

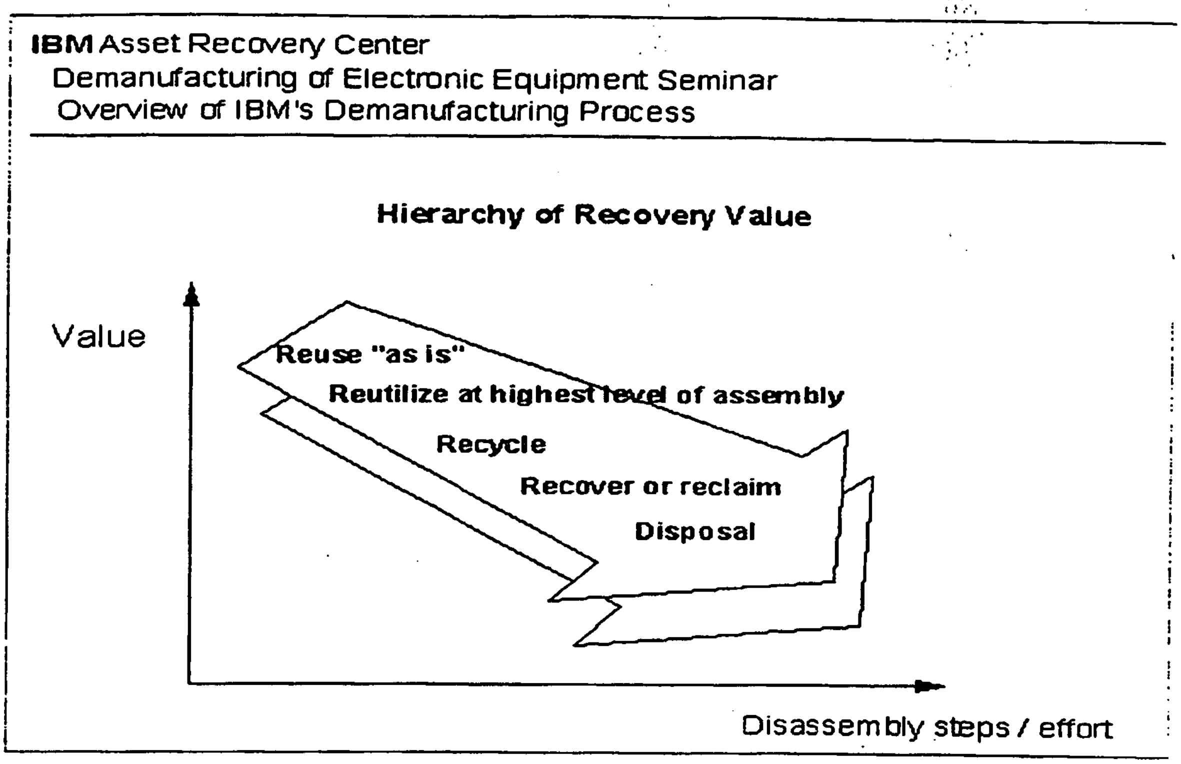

Figure 1

Process Overview

The entire demanufacturing process consists of 6 major steps or segments conducted on two lines. One line handles large computers or machines and desktop units while the other line concentrates on parts, software, or small computers like laptops. However, both lines use the same generic process. The key steps in the process are:

1. Customer shipment
2. Receipt
3. Stage
4. Disassembly
5. Commodity sort and grade
6. Ship for recovery / disposal

Figure 2 shows an overview diagram of the process.

Overall Demanufacturing Flow

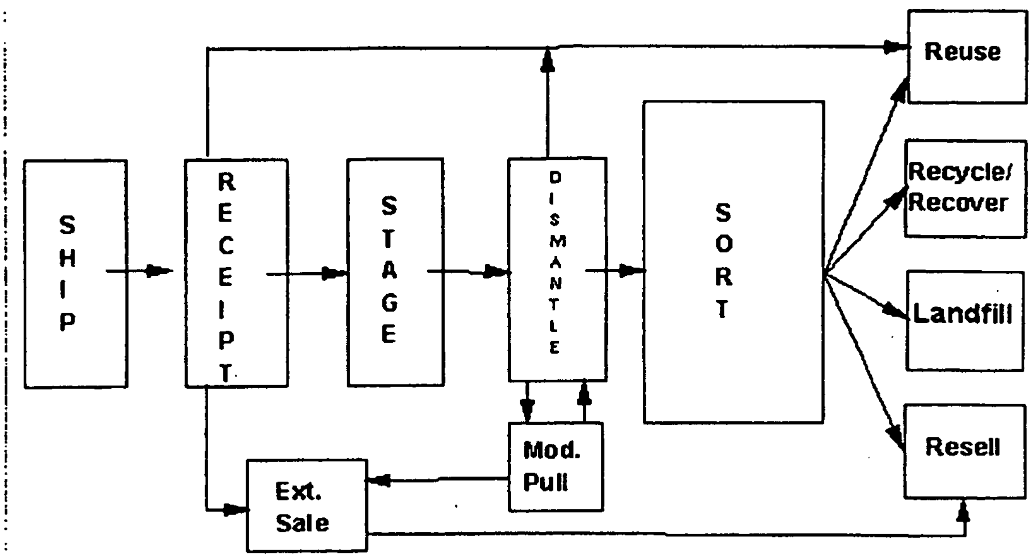

Figure 2

Step 1. Customer Shipment

The first step in the process is the initial contact that the Recovery Center makes with the customer. Experience has shown that the more information known about the material itself and any special customer requirements before shipment, the easier it is to process upon arrival. Customer representatives interface with the customer to insure understanding of the shipment(s) contents, any special requirements, and schedule. They also route the load to the appropriate demanufacturing line. An "Advanced Ship Notice" is then generated that assigns a unique customer tracking code / number that identifies the carrier and schedule, and lists any special customer requirements, like detailed inventory or processing timetables. This notice is put into a software system that allows appropriate personnel access for needed information.

Step 2. Receipt

The next step is the receipt process. This process occurs on the dock where the shipment is unloaded and verified. In some cases, a detailed inventory is conducted, other times a pallet or weight check suffices. If there are any discrepancies in shipment content, the shipment is put "on hold" and resolved with the customer before subsequent processing. When the shipment is

accepted, the customer representative acknowledges and confirms receipt with the customer and the load is prepared for processing by applying bar-coded labels on all pallets or machines. The labels uniquely identify the shipment and load to the appropriate customer tracking code indicated in the Advance Ship Notice [2].

Dock personnel also do a "quick sort" to identify items for potential reuse or external sale, and to separate any readily available scrap, trash, or commodities.

Step 3. Stage

The staging process allows the operation to properly segregate and batch the equipment or material for extended and more efficient runs in the actual demanufacturing area. Obviously, greater efficiency can be gained in disassembly by setting up workstations and dismantle teams to work similar equipment for longer periods of time. Lead technicians in the disassembly area use system generated information to identify and pull in work with similar content to minimize product changeover.

The staging operation and area are also used to process some of the easy, "quick sort" items identified in the receipt process, like parts for external sale or "as is" reuse machines. Doing this sort before moving equipment to the main disassembly area also aids in overall efficiency as double handling is reduced and work content becomes more "pure" while dismantling.

Step 4. Disassembly and Step 5. Commodity Sort and Grade

The disassembly process is where the majority of the demanufacturing work takes place. Here trained operators dismantle the equipment to the appropriate level of tear down to maximize recovery to IBM by saving parts for IBM field use, saving industry standard parts for OEM sale, and sorting to the right commodity group for recycling and/or disposal. Parts that have not been pre-approved for resale are impaired to protect assets from unauthorized reuse.

Throughout the dismantle process, emphasis is placed on the operators to use 2 to 4 person teams to reverse disassemble the equipment or material. Almost all items can be reverse disassembled if examined closely. Using this methodology, efficiency is gained by less tool changeover. It also improves the complexity control over dismantle whereby newly trained operators can be placed on less complex tasks and more experienced operators applied to the more detailed or complex tasks.

Figure 3. shows the workstation set up used in dismantling midrange to large systems. Here the machine is placed in the center of the work area so operators can access it from 360 degrees as the work piece is too large to swivel or move around. Operators sort material for save parts and commodities as the machine is being disassembled.

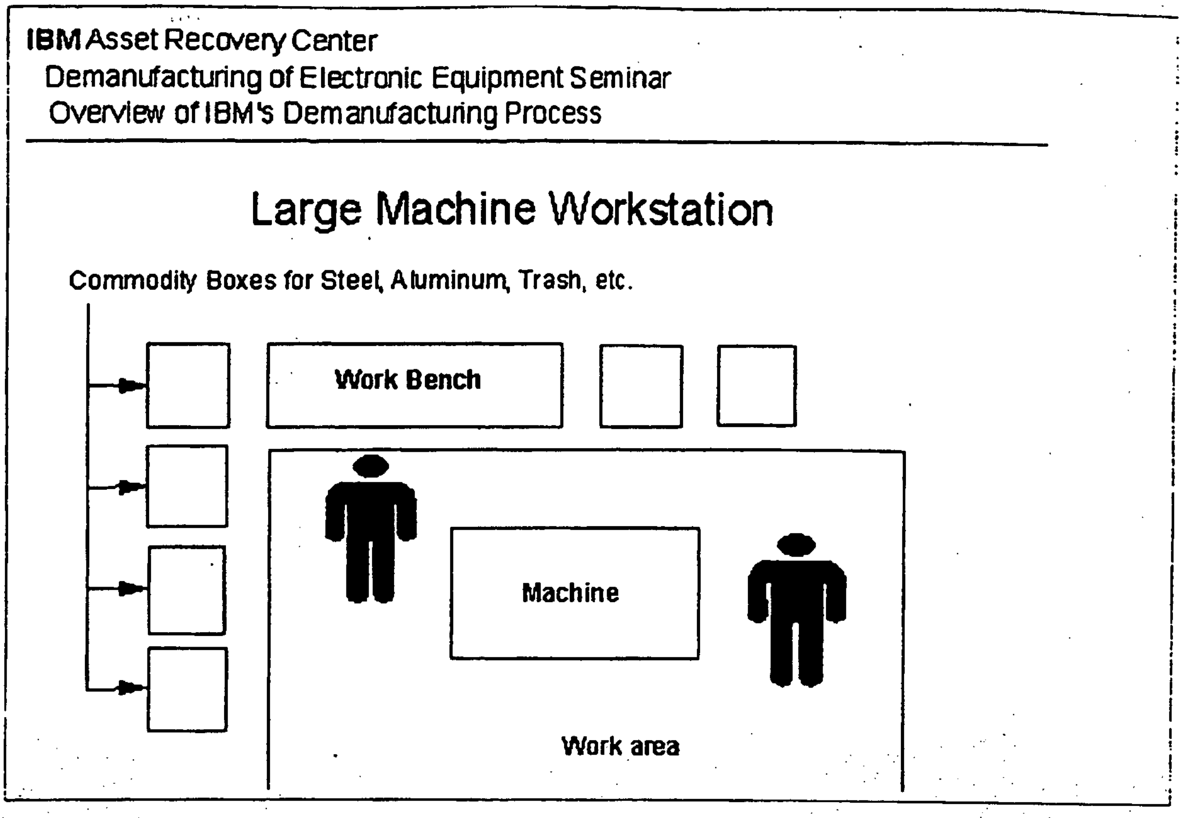

Figure 3 [3].

Processing desktops, which are lighter and smaller, are dismantled by 2 to 3 person teams using a small section of roller conveyor. Here an operator performs 2 to 3 dismantle and sort tasks and then slides the work piece down to the next operator who does the same until the work is consumed and properly sorted. Figure 4 shows the layout of this workstation.

The work area for processing parts, software, and/or laptops is shown in figure 5. Here the workstations are a series of work benches linked together next to a tiered conveyor. Again, a team of operators reverse disassemble the work in distinct, repetitive tasks and place the commodities such as plastic covers, cards, cables, ferrous and nonferrous material onto the lower conveyor. The conveyor then moves the material to a different conveyor loop at the end of the workstations were a trained material identification operator sorts material into proper commodity pallets. Paper, foam, and other items are placed on the upper conveyor and moved to another conveyor loop at the opposite end of the workstations where sorting also occurs.

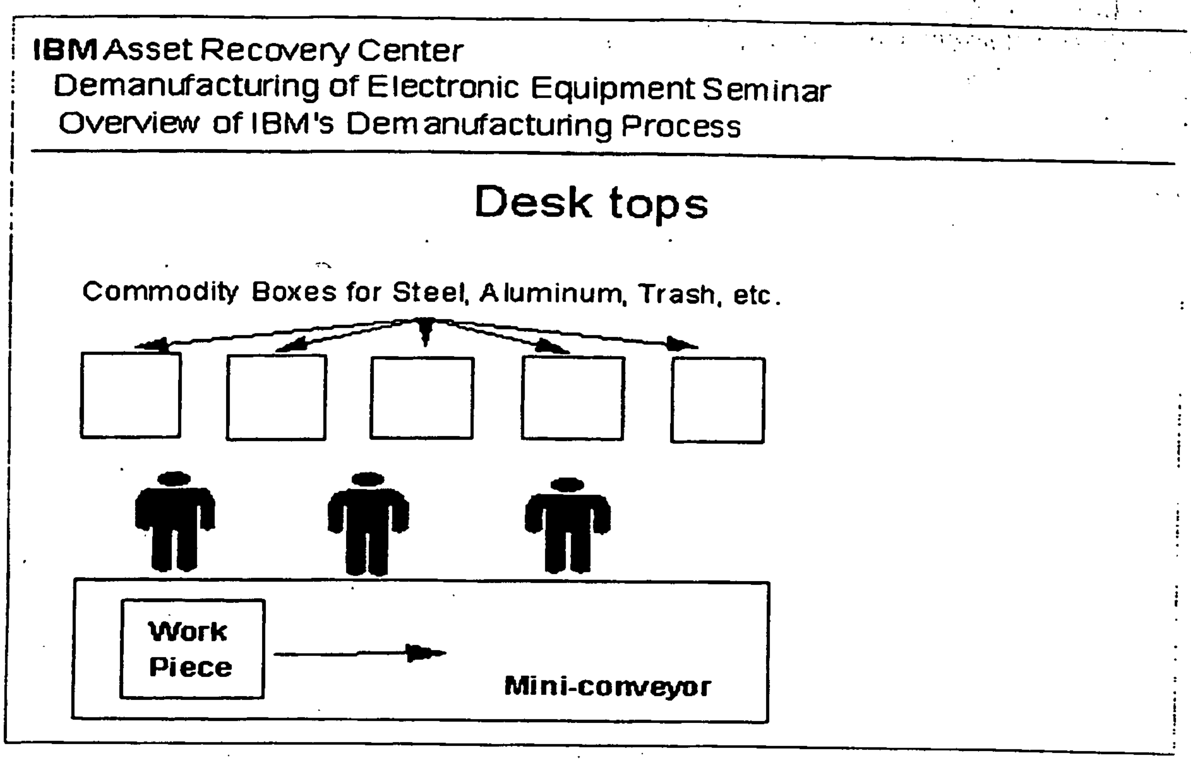

Figure 4.

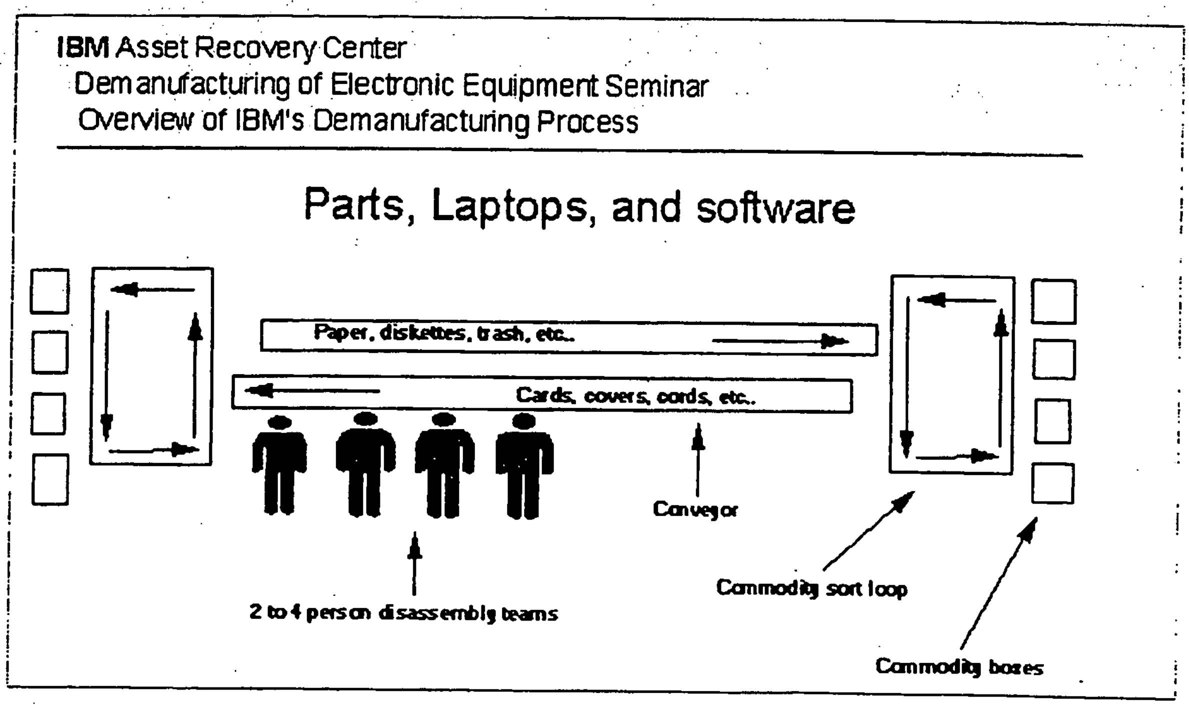

Figure 5 [4].

Step 6. Ship for Recovery / Disposal

As the disassembly of the work continues, the commodity pallets are filled and removed from the floor to dock area for staging. When sufficient commodity material is accumulated, a truck is scheduled for shipment to a vendor or broker for further recovery. Parts that are saved for internal or IBM field reuse are moved to designated locations for subsequent processing or reuse.

Additionally, when the entire Bill of Lading for a customer has been worked or demanufactured, the customer representative notifies the customer that his shipment has been processed. Data on cycle time, commodity content, and weight are then entered into the system for future planning purposes.

Results to date show that approximately 77% of the incoming material gets recycled and recovered, slightly greater than 15% gets reused, and less than 8% gets land filled.

Future Activities

The Asset Recovery Center continues to work with IBM's Engineering Center for Environmentally Conscious Products in Raleigh, North Carolina. Periodic workshops allow data to be fed forward on disassembly, commodity, or recyclability and recovery problems. In turn, the Engineering Center works with product designers, procurement, material, and packaging engineers to develop future products that allow greater reuse, increased recyclability, and easier and more efficient disassembly. This closed loop system ensures continuous emphasis on product end of life processing as well as environmentally conscious products.

Reference

[1] [2] [3] [4] [5] E. Grenchus, R. Keene, C. Nobs, "Demanufacturing of Information Technology Equipment", 1997 IEEE International Symposium on Electronics and the Environment, May 5-7, San Francisco, Calif.

A Model for Optimizing the Assembly and Disassembly of Electronic Systems

Peter A. Sandborn, *Member, IEEE,* and Cynthia F. Murphy

***Abstract*—This paper presents a methodology that incorporates simultaneous consideration of economic and environmental merit during the virtual prototyping phase of electronic product design. A model that allows optimization of a product life cycle, which includes primary assembly, disassembly, and secondary assembly using a mix of new and salvaged components, is described. Optimizing this particular life cycle scenario is important for products that are leased to customers or subject to product take-back laws. Monte Carlo simulation is used to account for uncertainty in the data, and demonstrates that high-level design and process decisions may be made with a few basic metrics and without highly specific data sets for every material and component used in a product. A web-based software tool has been developed that implements this methodology.**

***Index Terms*— Design-for-environment, design-to-cost, disassembly, electronics product take-back, end of life, recycling, virtual prototyping.**

NOMENCLATURE

Quantities associated with specific process steps and the entire unit assembly:

Buy back fraction	Fraction of the primary assembly cost paid to reacquire primary assemblies for recovery (per assembly).
$\mathrm{Cost}_{\mathrm{assembly\ step}}$	Cost of performing a single assembly process step (per unit assembly).
$\mathrm{Cost}_{\mathrm{buy\ back}}$	Allocated buy back cost (per assembly).
$\mathrm{Cost}_{\mathrm{cumulative}}$	Cumulative cost of all preceding assembly and test steps (per unit assembly).
$\mathrm{Cost}_{\mathrm{primary}}$	Cost of manufacturing the primary assembly (per unit assembly).
$\mathrm{Cost}_{\mathrm{test\ step}}$	Cost of performing a single test step (per unit assembly).
Fraction returned	Fraction of the primary unit assemblies returned for recovery that are salvageable.
Number of primary unit assemblies	Total number of primary unit assemblies to be manufactured.
Number of secondary unit assemblies	Total number of secondary unit assemblies to be manufactured.
Pass $\mathrm{fraction}_{\mathrm{assemblies}}$	Fraction of unit assemblies that are passed by a test step.
$\mathrm{Quality}_{\mathrm{assembly\ roll\ up}}$	Cumulative probability of defects not being introduced to the unit assembly as a result of all preceding assembly steps.
$\mathrm{Quality}_{\mathrm{step}}$	Probability that the unit assembly is not defective at the conclusion of an assembly step.
Scrap_n	Fraction of unit assemblies entering the nth test step that are scrapped by the nth test step.
$\mathrm{ScrapCum}_n$	Cumulative fraction of the unit assemblies that started the assembly process that have been scrapped after the nth test step.
Secondary build ratio	Ratio of secondary to primary unit assemblies manufactured.
Test effectiveness	Probability of a test step accurately identifying a defect in a part or unit assembly.
$\mathrm{Used}_{\mathrm{assembly}}$	Cumulative material used by all preceding process steps (per unit assembly).
$\mathrm{Used}_{\mathrm{step}}$	Material used by one assembly step (per unit assembly).
$\mathrm{Waste}_{\mathrm{assembly\ after\ test}}$	Total material wasted after a test step (per unit assembly).
$\mathrm{Waste}_{\mathrm{assembly\ before\ test}}$	Total material wasted prior to a test step (per unit assembly).
$\mathrm{Waste}_{\mathrm{step}}$	Material wasted by one assembly step (per unit assembly).

Quantities associated with specific parts (components/subcomponents of the unit assembly):

$\mathrm{Cost}_{\mathrm{attach}}$	Cost of attaching a single instance of a part.
$\mathrm{Cost}_{\mathrm{new\ part}}$	Cost of a single instance of a new (not salvaged) part.
$\mathrm{Cost}_{\mathrm{test}}$	Cost of testing a single instance of a part.

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$\mathrm{CostAvg}_{\text{all parts}}$	Average cost per single instance of a part (combination of new and salvaged parts).[1]
$\mathrm{CostAvg}_{\text{salvaged parts}}$	Average cost per single instance of a part recovered from salvaged unit assemblies.[1]
$\mathrm{Defects}_{\text{attach}}$	Probability of a defect occurring when attaching a single instance of a part to the assembly.
f	Fraction of parts in the secondary assembly that came from salvaged primary assemblies.
$\text{Pass fraction}_{\text{parts}}$	Fraction of salvaged parts that are passed by a test step.
$\mathrm{Quality}_{\text{disassembly}}$	Probability that the current disassembly step does not produce a defect in the part being removed.
$\mathrm{Quality}_{\text{disassembly roll up}}$	Cumulative probability of defects not being introduced to a part at each of the preceding assembly steps.
$\mathrm{Quality}_{\text{new part}}$	Probability that a new part is not defective.
$\mathrm{Quality}_{\text{post use}}$	Probability that a component is not defective after primary life, prior to disassembly.
$\mathrm{Quality}_{\text{post use}}$	Probability that a component is not defective after primary life, prior to disassembly.
$\mathrm{QualityAvg}_{\text{all parts}}$	Average probability that a part is not defective (combination of new and salvaged parts).[1]
$\mathrm{QualityAvg}_{\text{salvaged parts}}$	Average probability that a part recovered from a primary assembly and retested is not defective.
Quantity	Quantity (number of instances) of a specific part assembled by an assembly step.
$\mathrm{Used}_{\text{attach}}$	Material used when attaching one instance of a part.
$\mathrm{Used}_{\text{new part}}$	Material used when fabricating one instance of a part.
$\mathrm{UsedAvg}_{\text{part}}$	Average material used when including one instance of a part in the unit assembly.[1]
$\mathrm{Waste}_{\text{attach}}$	Material wasted when attaching one instance of a part.
$\mathrm{Waste}_{\text{new part}}$	Material wasted when fabricating one instance of a part.
$\mathrm{WasteAvg}_{\text{part}}$	Average material wasted when including one instance of a part in the unit assembly.[1]

[1] These quantities are the effective quantities per part, averaged over a large number of parts. New and salvaged parts are assumed to be tested to the same quality level.

I. Introduction

MOST products are optimized for manufacturability, and costs are minimized under the assumption of only a single or "primary" life. When the primary life of the product is over, the original equipment manufacturer (OEM) of the product is rarely involved with the product again. With the advent of more stringent product take-back laws in Europe and those on the horizon in the United States [1], OEM's of many products are being forced to contend with a significant percentage of the products being returned to the OEM at the end of the product's primary life. OEM's also contend with the return of products when the product is leased to the customer for a finite period of time. Under these circumstances, the OEM must consider the cost associated with end of life (EOL) scenarios when performing design tradeoffs and considering the product's life cycle costs. Possible EOL scenarios include resale, remanufacturing, recycling, disposal, and refurbishing.

An increasing number of products are being designed with the secondary lives taken into account, e.g., photocopiers [2], telephones, video cassettes recorders, and televisions [3]. For the purposes of the analysis presented here, a secondary life is considered to be the reuse of some or all of the components in the primary assembly to build a second identical product; any of the primary components that are not reused in the secondary assembly are disposed of. The universal application of this approach, not considered in this paper, is the reuse of components in many products including identical, similar, or perhaps significantly different products. The challenge is to determine, on an application specific basis, what subset of components should be reused and what subset should be disposed of in order to minimize system costs. Several interdependent issues must be considered to properly determine the optimum component reuse scenario, including assembly costs, disassembly costs; defects introduced in the assembly, disassembly, and primary life use of the product; and the waste stream associated with the life cycle.

Two bodies of existing work are relevant to this paper. The first focuses on cost modeling associated with EOL strategies and the second is aimed at production planning and inventory control. EOL strategies that involve disassembly have been modeled many different ways. Approaches include, "scorecards" [4]; life cycle assessment (LCA) [5]; cost-benefit analysis [6]; activity-based costing (ABC) [7]; decision trees [8]; and high-level financial models [9]. An excellent review of disassembly analysis methods appears in [4]. All of these approaches have merit and have been successfully demonstrated. With the exception of financial models, these methods are usually applied to the disassembly process in isolation, i.e., no attempt is made to concurrently model the primary assembly and the EOL approach to optimize over a broader portion of the product life cycle. In the case of financial models, the entire life cycle is modeled, however, the assembly, disassembly, and testing costs are often characterized as single values, and the models do not include a treatment of specific component yields or address how the component yields are modified by primary use or disassembly processes.

TABLE I
INPUTS TO THE MODEL

Input Category	Input Characteristics
Materials and Components (all inputs are part specific)	• New part cost, quality, materials wasted and materials used in its fabrication • Cost of disassembly • Post primary use quality • Test cost and effectiveness
Assembly	• Process flow description (test and assembly steps) • Component attach costs, defects introduced, wasted and used materials • Test costs and effectiveness
Disassembly and Salvage	• Fraction of primary parts returned • Ratio of secondary to primary build quantities • Buy back requirements and costs • Disassembly process flow description • Defects introduced into components (per component per disassembly step)

The second class of existing work falls at the opposite end of the spectrum from the EOL cost models summarized above. These models treat the broader product life cycle, but at the expense of application-specific manufacturing and disassembly details. Several authors have developed rigorous models for production/inventory systems that include remanufacturing and disposal, for examples see [10] and [11]. The relevant concepts included in these efforts are their concurrent treatment of primary product manufacturing and remanufacturing, and the inclusion of production issues such as inventory levels, ordering information, time value of money, and lead time.

In the model presented in this paper, actual process models that automatically adapt to changes in component mix and component yields are used for assembly and disassembly modeling. In addition, material use and waste inventories are generated as a result of the process models. The model in this paper also optimizes over the entire primary assembly, disassembly, and secondary assembly life cycle. The objective of the model presented herein is similar to the work presented in [3]; however, this model is specifically designed to optimize component selection. We suggest that the work presented in this paper provides application-specific manufacturing cost, yield, and waste input to the existing high-level financial and cost-benefit models for "remanufacture" EOL scenarios, or as the core of a production/inventory model.

The methodology and model presented in this paper are targeted for use during "virtual prototyping" of electronic products. Virtual prototyping takes place at the earliest phases of the system design, prior to the start of traditional CAD activities [12]. Virtual prototyping starts with requirements and constraints, and results in a system specification for how to build the system (bill of materials, technologies, design rules, and materials). One of the characteristics of the virtual prototyping phase of the design process is that detailed descriptive data about the product and the manufacturing processes associated with creating it are not well defined. To obtain meaningful results, we use a Monte Carlo modeling approach that accommodates the characterization of input data as probability distributions. As a result, the outputs obtained from the models are also probability distributions. This approach allows us to draw valid design conclusions from uncertain design inputs.

II. MODEL

The model used for this analysis considers four stages in the life cycle of a product:

1) material and component acquisition;
2) primary assembly and test of the product using all new parts;
3) return and disassembly of the product after primary use;
4) secondary assembly and test of an identical product using a mixture of salvaged and new parts.

A. Formulation

The basic inputs to the model are listed in Table I. The secondary assembly uses the same process inputs as the primary assembly process.

The outputs of the model are cost, quality (yield), the amount of waste material generated, and the amount of material contained in the product. Standard accounting methods are used to accumulate cost and quality through the primary assembly processes. Test and/or inspection steps in the assembly processes are characterized by test efficiencies that account for test escapes (defective parts that are not identified during test).[2] In addition, defects introduced to components, other than the component being disassembled, at each disassembly process step can be modeled. If, for example, one part is salvaged only by destroying another, the probability of introducing defects to the destroyed part during disassembly would be 100%.

After completion of the disassembly process, components may either be disposed of, or salvaged and used in a secondary build of the product. The secondary assembly uses salvaged components supplemented with new components, the mix of which is driven by:

[2] In this model, we assume that the test activities do not erroneously reject good parts.

1) the ratio of the quantity of secondary products built to the number of original (primary) products built;
2) the fraction of the original product which is available for salvage;
3) the fraction of each individual component that are successfully salvaged during the disassembly process.

The cost and quality associated with a primary or secondary component assembly step are given by the following relations. Assuming only one type of part is attached per process step, the cost of an assembly process step associated with a component is

$$\text{Cost}_{\text{assemblystep}} = (\text{Quantity})(\text{Cost}_{\text{part}} + \text{CostAvg}_{\text{allparts}}). \tag{1}$$

The cost of the part ($\text{CostAvg}_{\text{all parts}}$) being assembled in (1) is either $\text{Cost}_{\text{new part}}$ (primary assembly) or is given by (2) for the secondary assembly

$$\text{CostAvg}_{\text{all parts}} = (1-f)(\text{Cost}_{\text{new part}}) + f(\text{CostAvg}_{\text{salvaged parts}}) \tag{2}$$

where f is the fraction of parts in the secondary assembly that came from salvaged primary assemblies (f is derived below). In this model, the cost of a part salvaged from a recovered primary assembly and retested is only the cost of testing a single instance of the part ($\text{Cost}_{\text{test}}$), i.e., it does not contain a component cost. This is appropriate because, the cost of obtaining the entire used primary assembly from the customer and performing all required disassembly is used as the starting point for the secondary assembly process and contained within this cost is the cost of obtaining individual salvaged components. Note, even if the OEM purchases the components of interest back from an asset manager or broker, the broker sets the price of the salvaged component based on obtaining the whole assembly from the customer and performing the disassembly.

The fraction of parts in the secondary assembly that come from salvaged primary assemblies is computed using

$$f = \min\left[\frac{(\text{fraction returned})\,(\text{pass fraction}_{\text{parts}})}{(\text{secondary build ratio})}, 1\right]. \tag{3}$$

Where "min" indicates that the smaller of the two quantities within the brackets in (3) is used. As denoted in (3), the value of f is not allowed to exceed one, i.e., it is assumed that take back is not legislated, and therefore, products whose parts are not required for secondary assemblies are not bought back or disassembled. The ratio of secondary to primary builds is given by

$$\text{secondary build ratio} = \frac{\text{number of secondary unit assemblies}}{\text{number of primary unit assemblies}}. \tag{4}$$

The formulations of (3) and (4) are most accurate for mature products with constant annual production or products with short primary lives (<1 year), i.e., the approximations are less accurate for products whose annual production rates vary significantly and whose primary lives are multiple years. The fraction of salvaged parts that pass the test is given by

$$\text{pass fraction}_{\text{parts}} = [(\text{Quality}_{\text{post use}})\,(\text{Quality}_{\text{disassembly}}) \cdot (\text{Quality}_{\text{disassembly roll up}})]^{(\text{test effectiveness})} \tag{5}$$

where the interpretation of test effectiveness is the probability of the test or inspection activity successfully identifying a defect in a part.

The assembly cost for the primary build is computed using only (1). Equations (1)–(5) are used to compute the cost of a process step that assembles a component to the system during the secondary build.

The quality of the system after an assembly step is given by

$$\text{Quality}_{\text{step}} = (\text{QualityAvg}_{\text{all parts}}) \cdot (1 - \text{Defects}_{\text{attach}})^{\text{Quantity}}. \tag{6}$$

During the primary assembly, the part quality ($\text{QualityAvg}_{\text{all parts}}$) is given by $\text{Quality}_{\text{new part}}$, the probability that a new component is not defective. During the secondary assembly, the part quality is given by

$$\text{QualityAvg}_{\text{all parts}} = (1-f)\,(\text{Quality}_{\text{new part}}) + f(\text{QualityAvg}_{\text{salvaged parts}}). \tag{7}$$

The quality of a part salvaged from a recovered primary assembly and retested is given by[3]

$$\text{QualityAvg}_{\text{salvaged parts}} = [(\text{Quality}_{\text{post use}})\,(\text{Quality}_{\text{disassembly}}) \cdot (\text{Quality}_{\text{disassembly roll up}})]^{(1-\text{test effectiveness})}. \tag{8}$$

We also have a need to accumulate materials that are part of the product and materials that are wasted during the fabrication and assembly processes. We inventory the materials in the product and the material wasted and normalize the inventory to a single product. The quantity of material used and wasted by a process step is given by

$$\text{Used}_{\text{step}} = (\text{Quantity})\,(\text{UsedAvg}_{\text{part}} + \text{Used}_{\text{attach}}) \tag{9a}$$

$$\text{Waste}_{\text{step}} = (\text{Quantity})\,(\text{WasteAvg}_{\text{part}} + \text{Waste}_{\text{attach}}). \tag{9b}$$

The material added to the product for a part in (9a) is either $\text{Used}_{\text{new part}}$ (primary assembly) or is given by (10a) for the secondary assembly. Equation (10b) gives the analogous relations for material waste

$$\text{UsedAvg}_{\text{part}} = (1-f)\,(\text{Used}_{\text{new part}}) \tag{10a}$$

$$\text{WasteAvg}_{\text{part}} = (1-f)\,(\text{Waste}_{\text{new part}}) \tag{10b}$$

Note, unlike (2), (10) contains no second term multiplied by the fraction of salvaged parts. In (10), all materials used in, or

[3] The quality predicted by (8) is higher than the quality intuitively found if the test effectiveness referred to the probability that defective parts are identified by the test, instead of the probability that defects are identified by the tests. Equation (8) is derived by accounting for the possibility that a defective part could have more than one defect, but that the identification of any defects, not necessarily all defects, is enough to scrap the part, see [13].

wasted by, fabricating a salvaged part were already accounted for in the primary assembly the first time the part was acquired.

Test operations during assembly have a unique effect on the cost, quality, and waste materials (they do not affect the materials used per assembly). The effective cost of a test step (per unit assembly) is given by

$$\text{Cost}_{\text{test step}} = \frac{\text{Cost}_{\text{cumulative}} + \text{Cost}_{\text{test}}}{\text{pass faction}_{\text{assemblies}}} \tag{11}$$

where $\text{Cost}_{\text{cumulative}}$ is the cumulative cost of the assembly up to but not including the test step. The pass fraction appears in the denominator of (11) so that all the money spent on assemblies that do not pass the test is properly reallocated over the assemblies that pass the test. The fraction of assemblies that are passed by a test operation is similar to (5)

$$\text{pass fraction}_{\text{assemblies}} = [\text{Quality}_{\text{assembly roll up}}]^{(\text{test effectiveness})}. \tag{12}$$

The quality of assemblies passed by the test step is given by

$$\text{Quality}_{\text{step}} = [\text{Quality}_{\text{assembly roll up}}]^{(1-\text{test effectiveness})}. \tag{13}$$

Test steps do not modify the material content of the assembly, i.e., they neither add nor remove material from assemblies that they pass. However, since test steps scrap defective assemblies, the materials in the scrapped assemblies must be reallocated over the waste inventories associated with all the passed assemblies that continue through the process. The total waste per assembly is modified in the following way,

$$\text{Waste}_{\substack{\text{assembly}\\\text{after test}}} = \text{Waste}_{\substack{\text{assembly}\\\text{before test}}} + (1 - \text{pass fraction}_{\text{assemblies}}) \cdot (\text{Used}_{\text{assembly}}) \tag{14}$$

It is also useful to accumulate the fraction of assemblies that begin the assembly process that are scrapped by test steps throughout the process. The fraction of assemblies entering the nth test step that are scrapped by the nth test step is given by

$$\text{Scrap}_n = (1 - \text{pass fraction}_{\text{assemblies}_n}). \tag{15}$$

The cumulative scrap after the nth test step is given by

$$\text{ScrapCum}_n = (1 - \text{ScrapCum}_{n-1})(\text{Scrap}_n) + \text{ScrapCum}_{n-1} \tag{16}$$

ScrapCum_n represents the fraction of the assemblies that started the assembly process that have been scrapped after the nth test step.

The model is not presently designed to accommodate rework processes. A rework operation that followed a test step would repair some of the scrapped assemblies, resulting in a cost rebate and a reduction in the waste allocated to each assembly.

Buy back cost is defined as the cost of obtaining the used primary assembly from the customer. It is a combination of possible payment to the customer and any administrative or handling costs required to obtain the primary assembly and return it to the factory. Two buy back options are presently supported. The model will either assume that every primary assembly is repurchased, or that only the number of primary assemblies necessary to accommodate the desired number of secondary assemblies are repurchased. In the first case (all primaries repurchased), the allocated buy back cost per assembly is given by

$$\text{Cost}_{\text{buy back}} = \frac{(\text{buy back fraction})(\text{Cost}_{\text{primary}})}{\text{secondary build ratio}} \tag{17a}$$

if only the minimum number of primary assemblies are repurchased

$$\text{Cost}_{\text{buy back}} = \frac{(\text{buy back fraction})(\text{Cost}_{\text{primary}})}{\text{fraction returned}} \tag{17b}$$

$\text{Cost}_{\text{buy back}}$ is added to the disassembly cost associated with a single primary assembly and used as the starting cost for a secondary assembly.

The model, as currently constructed, assumes that the primary and secondary builds are identical products. While not shown or discussed here, the model could easily be restructured to accommodate a secondary build that produces a similar or a completely different product.

B. Uncertainty Analysis

The target for the model presented in this paper is the "virtual prototyping" of an electronic product or system. Virtual prototyping is performed at the earliest phases of the design process before detailed physical design (layout and routing) is done, and inputs are often little more than a bill of materials and packaging technology choices. Because minimal information is available at this point in the design, and the information that is available includes substantial uncertainties, a careful treatment of those uncertainties is necessary to obtain meaningful analysis results.

In order to facilitate making design and process decisions with only a few basic metrics and without highly specific data input sets for every material and component used in a product, the present model treats uncertainties by allowing each input to the equations outlined in the previous section to be optionally represented as a probability distribution rather than a single fixed value. Supported distributions include normal, lognormal, triangular, and uniform. For example, in the case of the quality of an incoming part, experience with the supplier and the part suggests a most likely value for the incoming yield, but different shipments of parts may have yields that are slightly higher or lower. If distributed values are entered, a Monte Carlo analysis is performed. During the analysis, the model will randomly select values within the defined distributions for a specified number of samples, or as many samples as are necessary to meet a specified confidence level.

A triangular distribution (Fig. 1) is included as an option because both the minimum and maximum values that can be produced by the distribution are controllable [14] (the analysis reported in [15] also used triangular distributions). This control is important when modeling inputs where it does not make sense to have any samples in a distribution that are less than zero (which applies to most of the quantities modeled in this paper) or greater than one (or 100%), which

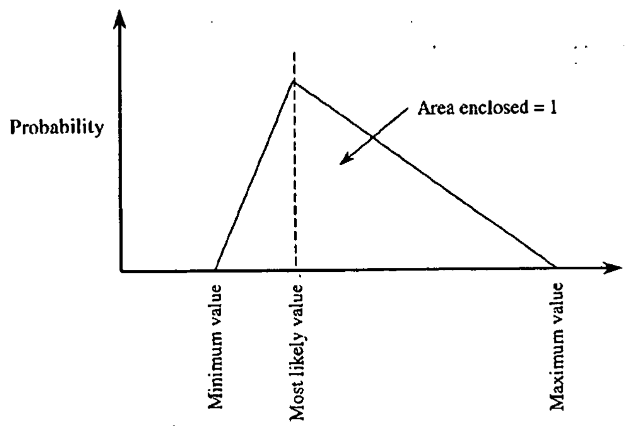


Fig. 1. Example triangular distribution that can be used to describe input data.

applies to all yield and quality values. Using another type of distribution (normal for example) to represent a yield with a most likely value of 98% would always result in some samples that have values greater than 100% causing the analysis results to be skewed. Alternatively, using a normal distribution and disallowing nonphysical sample values, results in effectively using a distribution that is not a valid probability distribution (i.e., the area under the distribution is not one). There are often known external constraints to the values as well, such as maximum allowable cost imposed by a purchasing department. For these reasons the triangular distribution is very useful.

If one or more of the input values are defined as a probability distribution, one or more of the final metrics that describe the system will be a probability distribution rather than a single value. The width of the resulting distribution provides a measure of the sensitivity of the computed metric to the uncertainties in the data inputs. We chose to treat uncertainties using a Monte Carlo method because of its ease of application to our set of equations and its inherent generality. Other related efforts that use Monte Carlo approaches include uncertainty modeling associated with environmental performance scoring [15], and activity-based disassembly cost modeling [7]. Alternative approaches to treating uncertainties in input data have the advantage of being computationally faster, but are not as general; these approaches include embedding probabilistic distribution factors within the analysis [16].

C. Implementation

The model was implemented as a web-based software tool using Java. The tool is designed to be accessed over Internet or Intranet connections. This allows for both internal and external sharing of data and information, such as between supplier and manufacturer. Several examples from the tool data input interface are shown in Fig. 2. A process, similar in construction to the one shown in Fig. 2(b), can be defined for disassembly. The disassembly process need not be related to the assembly process. The distributions for input data can be defined independently (i.e., each input can have its own unique distribution). Fig. 3 shows an example output from the analysis tool. Each output is potentially represented by a distribution like the one shown in Fig. 3.

III. Example Analysis

A flat panel display (FPD) was selected to demonstrate the methodology outlined in Section II; however, this methodology is not limited to this particular electronic product or even to electronic products in general. The implementation of the model presented in this paper is bounded by what is within the control of a single manufacturer, but the methodology (and model) could be expanded to capture the entire life cycle of the product. For the sake of simplicity, this example assumes that the only end of life (EOL) activity is reuse of components within an identical product design. In actual use, the model could be expanded to include other secondary products and other EOL processes, including materials recycling.

A. Description

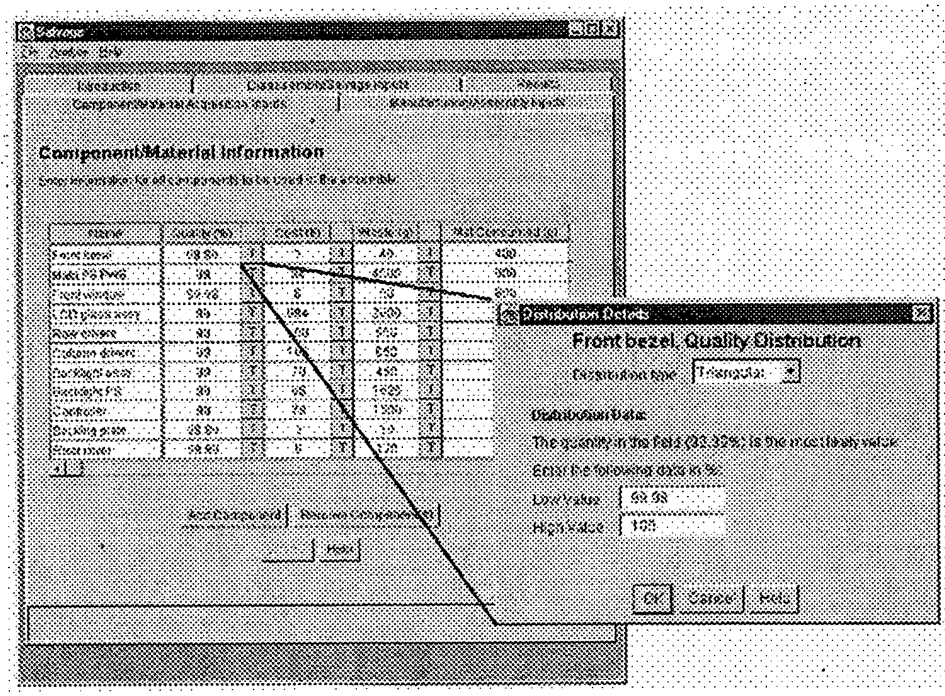
A flat panel display (FPD) was selected for demonstrating this methodology for a number of reasons. First, it provides an opportunity to examine a product that is expected to increase dramatically in market share, but that has undergone relatively little EOL assessment. Second, the Microelectronics and Computer Technology Corporation (MCC) has conducted detailed studies of FPD's, which provides a sound data foundation for this analysis [17]. Third, high intrinsic value of certain FPD components (e.g., IC devices and liquid-crystal display assemblies) make this a reasonable target for future efforts to recover value at EOL. A preliminary disassembly analysis of this FPD appeared in [18].

Component description and data was derived from an actual teardown of an FPD [17]. In the case of the FPD being analyzed, the bill of materials actually consists of well over 100 different parts. However, for the purpose of simplifying the analysis, the product was divided into 11 high-level components and the data combined to reflect those divisions.

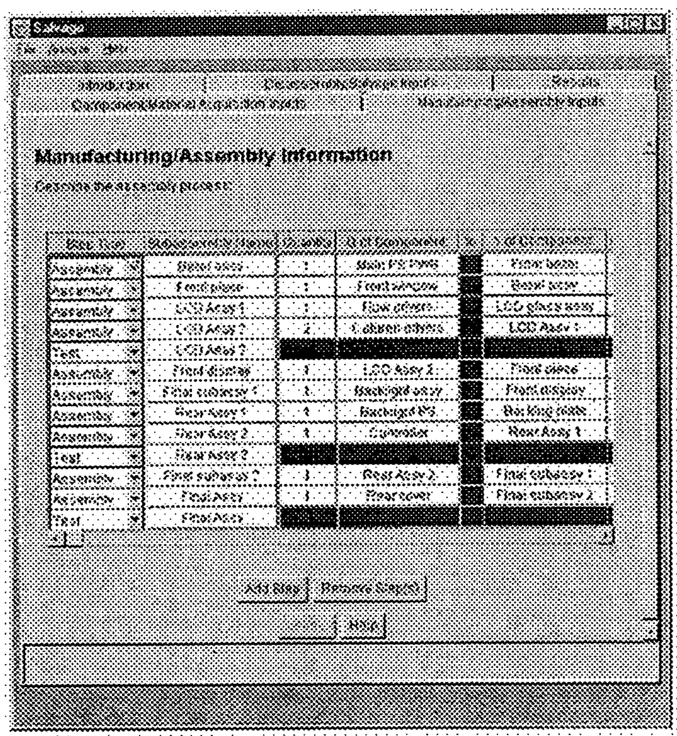
Portions of the FPD were grouped to capture components reflecting the sub-system level at which they might be purchased. These components or sub-components are typically simple to assemble and disassemble (using screws and clamps) and therefore might realistically be salvaged intact for reuse. If the analysis was focused on disassembly for recycling or for reuse in a completely different product, the components would be grouped differently.

Fig. 4 illustrates the rough layout of the components used in this analysis. Fig. 5 is a photograph of the interior of the actual FPD. Table II shows the list of components used in the FPD assembly, with the most likely values for the four basic inputs used.

The cost and composition (mass) of the components are likely to be known at the time of purchase. However, there may still be some fluctuation. These inputs were therefore entered with ±10% triangular distributions. Although the analysis shown here lumps all materials together and gives a cumulative mass, in actual practice the amount of materials of interest would be inventoried separately.



(a)



(b)

Fig. 2. Example user interface for entering inputs into the modeling tool. (a) Component input table. The buttons (labeled with "T" for triangular distribution) are associated with the input field to their left. Pressing on these buttons provides the user with the option of including distribution data. (b) Assembly process input table.

The quality of the component may or may not be known. Typically a minimum quality will be specified by the supplier and a most likely value can be estimated by the manufacturer given any prior experience with the product. In this analysis, the values given in Table II are entered as the most likely value (based on engineering knowledge for this general part

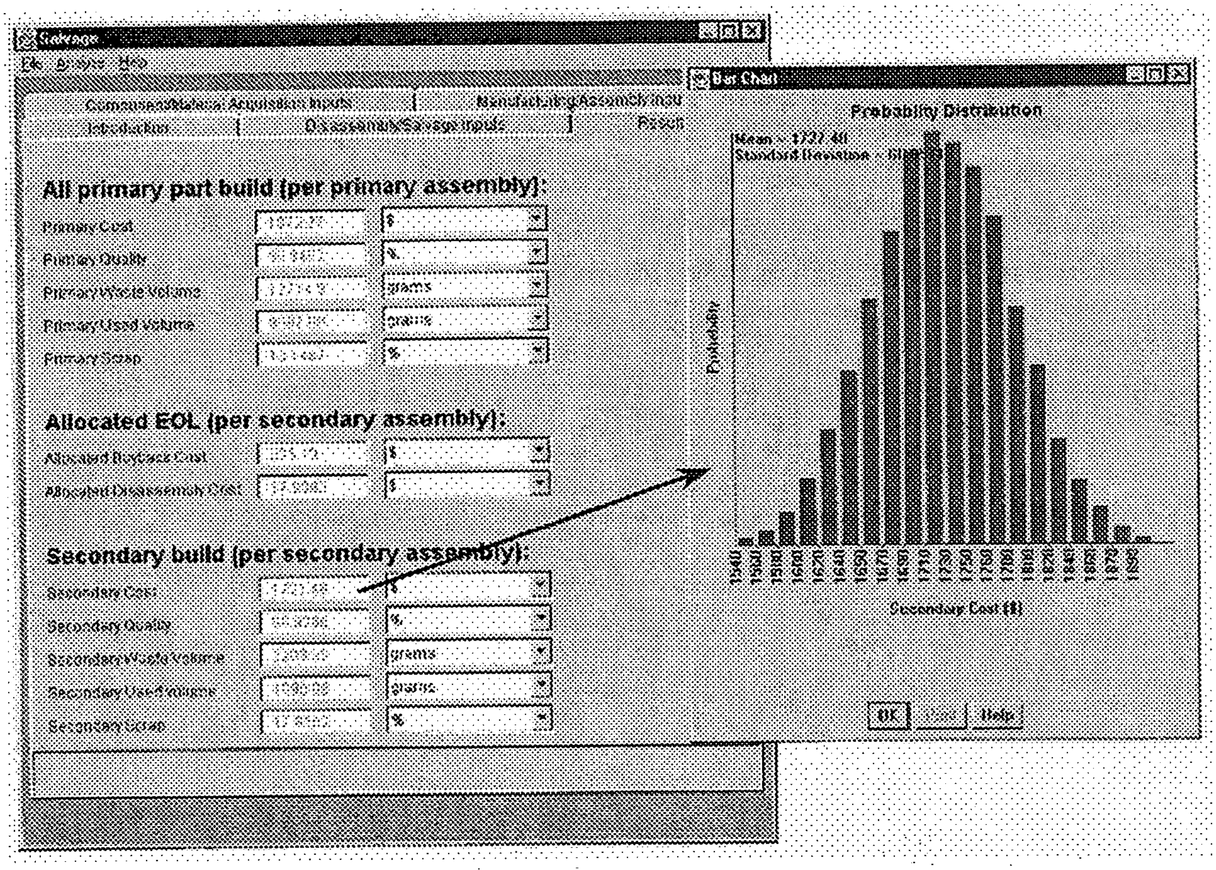


Fig. 3. Example results output interface for the modeling tool. Distributions may be plotted for any of the result fields.

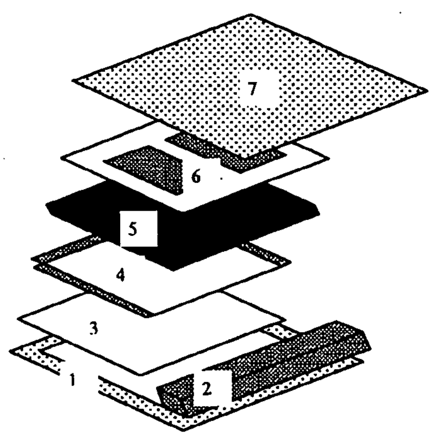


Fig. 4. Schematic layout of flat panel display (FPD) components used in this analysis.

type), with an upper bound of 100% and a lower bound that makes the distribution symmetric.

The waste generated in producing the product may or may not be known; even if it is documented, the data may not be made available from the supplier. Regardless, educated guesses can typically be made for different product families (injection-molded plastic, PWB's, IC's, etc.). The accuracy of these values will depend upon the type of data generally available and/or the ability to generate data using predictive models. For the analysis shown, the most likely value has been entered based on the type and mass of component (or parts of the component) and the triangular distribution is set at $\pm 25\%$.

B. Primary Assembly Analysis

Consider only the primary assembly of the FPD first. Performing an analysis with the data described above (10 000 samples evaluated) gives the results shown in Table III.

Table III shows that even when the values of waste for incoming components have up to a $\pm 25\%$ error, the final result has a relatively low error (<10% at the 95% confidence level). This is partially due to the use of values for process waste generation from within the company (i.e., during the assembly process) over which the manufacturer has control and for which there is high confidence data.

While Table III is a useful illustration of data confidence, the model may also be used to optimize waste (or other metrics) when there are tradeoffs in selecting a particular component. For example, suppose a supplier offers a component with

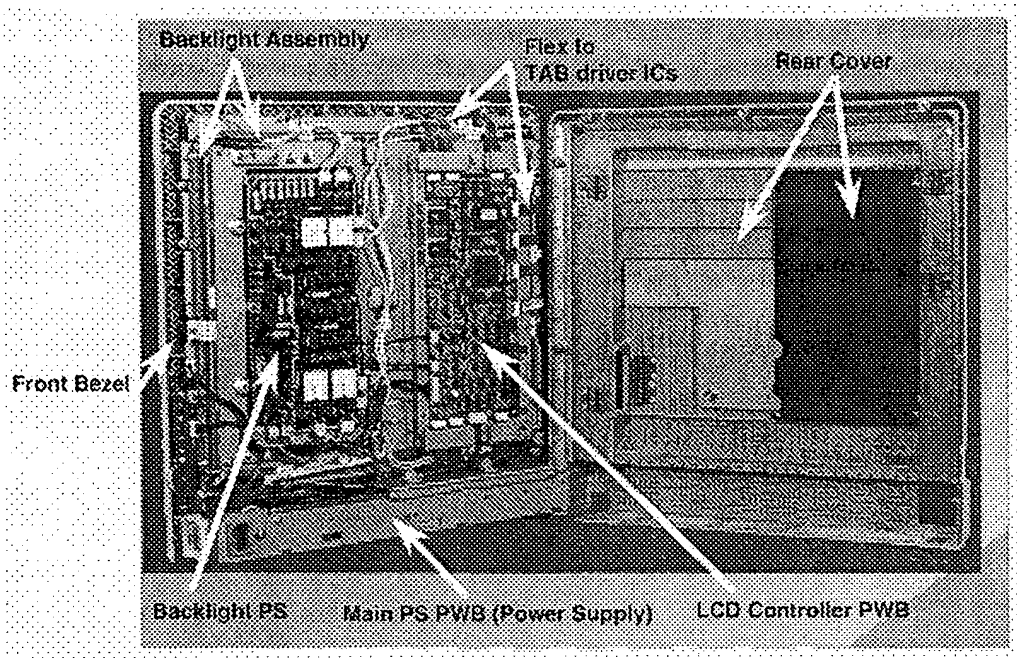


Fig. 5. Photograph of the flat panel display.

TABLE II
INPUTS TO THE FPD ANALYSIS

Component	Type*	Quality (%)	Cost ($)	Mass (g)	Waste** (g)
Front bezel	Mechanical	99.99	3	400	40
Main PS PWB	Electrical	99.00	34	900	4500
Front window	Mechanical	99.99	6	800	80
LCD glass assy	Glass	99.00	994	400	2000
Row drivers	Electrical	99.00	100	55	550
Column drivers	Electrical	99.00	186	65	650
Backlight assy	Glass	99.00	70	4350	450
Backlight PS	Electrical	99.00	66	325	1625
Controller	Electrical	99.00	78	150	1500
Backing plate	Mechanical	99.99	3	100	10
Rear cover	Mechanical	99.99	9	1200	120

* The component type is used to segregate salvage options in Table V.
** Waste is the volume of waste produced when manufacturing this component.

TABLE III
OUTPUTS THROUGH PRIMARY ASSEMBLY

	Mean	Standard Deviation	% Standard Deviation	95% Confidence Range
FPD Final Quality	99.95%	0.02%	0.02%	99.91 - 99.99%
FPD Final Cost	$1,972	$52.50	2.66%	$1,867 - $2,077
FPD Cumulative Waste (g)	12679	566	4.46%	11547 - 13811
FPD Material Consumed (g)	9000	193	2.14%	8614 - 9386

lower incoming waste, but lower guaranteed quality. Since the lower quality will result in increased scrap, the designer might wish to determine the amount of component waste reduction required to achieve an overall waste reduction for the product. An example of this type of tradeoff analysis for the backlight assembly portion of the FPD is presented in Fig. 6. Average incoming waste for the backlight assembly is plotted versus the cumulative FPD waste for two different quality levels. The graph shows that incoming waste for the backlight assembly must drop to less than 85% of the original backlight assembly

TABLE IV
HIGH QUALITY VERSUS LOW COST ASSEMBLY COMPARISON

	% Units Passed by Final Test*	FPD Final Quality	FPD Material Consumed (g)	FPD Cumulative Waste (g)	FPD Final Cost ($)
High Quality Assembly	92.20%	99.98%	9000	12400	$1,885
Low Cost Assembly	86.85%	99.95%	9000	12679	$1,972
Delta	5.35%	0.03%	0	-279	-$89
% Delta	6.16%	0.03%	0%	-2.20%	-4.49%

*Percentage of units that begin production that are passed by the final test.

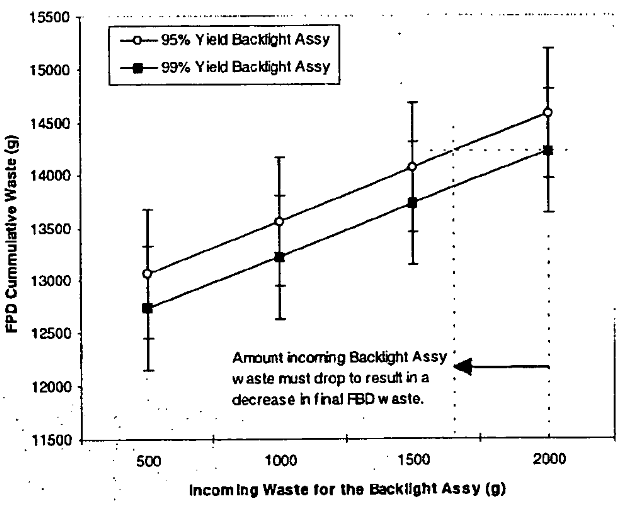


Fig. 6. Cumulative FPD waste versus the incoming waste for the backlight assembly for two different backlight assembly incoming qualities.

(assuming a 99% to 95% change in incoming quality) in order to decrease the overall waste generation for the FPD.

The model may also be used exclusively within the design and manufacturing environment. An example of two different assembly options is used to demonstrate this application. Assume that there are two assembly lines available. One costs an average of $1.50 per step (labor, equipment, and materials). The second costs an average of $3.00 per step but results in two orders of magnitude increase in quality (i.e., 100 ppm defects drops to 1 ppm). As in the example given in material and component acquisition, only the primary assembly is considered. A comparison of the two assembly lines appears in Table IV.

In this case, three of the four metrics improved by going to the higher quality assembly, primarily because of decreased scrap. The outgoing quality increases slightly and the number of units that must begin production decreases by more than 5%. Although assembly costs increase by $15, the final cost of producing a flat panel decreases by $89. Total waste drops by 2% (less scrap from test steps). The material consumed does not change because the same amount of material is present in a "passed" assembly in both cases.

C. Disassembly and Secondary Assembly Analysis

The end-of-life scenario modeled in this paper is a combination of remanufacture and disposal that examines a secondary build of the same FPD using components from the original build. After the primary units are repurchased or otherwise reacquired by the OEM at some fraction of the original cost (for this analysis assumed to be 5%), the product is disassembled. Since these particular components are fairly simply assembled with screws and clamps, the disassembly is assumed to be equally simple with an average cost of $1.50 per component and greater than 95% yields. It was also assumed that the individual components were in good working order at the time of return with 85% of the electronics functioning and 90% of the display components still usable. The ability to avoid using poor quality components in the secondary product, is reasonably good, with test efficiencies ranging from 80 to 90%. The ratio of secondary to primary builds is 0.25.

Given the assumptions above, the four basic metrics were examined for both the primary and secondary build. The cost distributions at the 99% confidence level (3 σ) indicate that there is a clear economic advantage to using reclaimed components. Assuming all the primary assemblies are repurchased, the average cost drops from $1972 per unit to $1727 per unit (Fig. 7), when buy back and disassembly costs are allocated to the secondary assemblies. The outgoing quality is approximately unchanged at 99.95%. Total cumulative waste is reduced from 12.7 to 2.2 kg and material consumed drops from 9.0 to 1.1 kg. It can be seen from this example that highly specific data and exact numbers may not be required for basic business decisions. Given the above assumptions and data distributions, it appears that salvage of components from this FPD is worth further consideration. In a real situation, finalization of the design and manufacturing strategy would require more detailed and specific data, but the initial analysis, gives the business unit reason to pursue a more detailed life-cycle assessment.

One of the advantages of the methodology presented in this paper is the ability to perform sensitivity analyzes. In order to demonstrate this, the cost to build a flat panel display from salvaged parts is plotted against the buy-back cost [Fig. 8(a)]. Error bars (1 σ) are also plotted. The results show that if buy back costs exceed 8% of the primary assembly cost (and all primary assemblies are repurchased), that a secondary assembly using salvaged parts is not economical. The economics of secondary assembly are considerably better if only enough primary assemblies are repurchased to satisfy the secondary assembly requirements (even with 20% buy-back costs, the cost to build a refurbished FPD may be lower

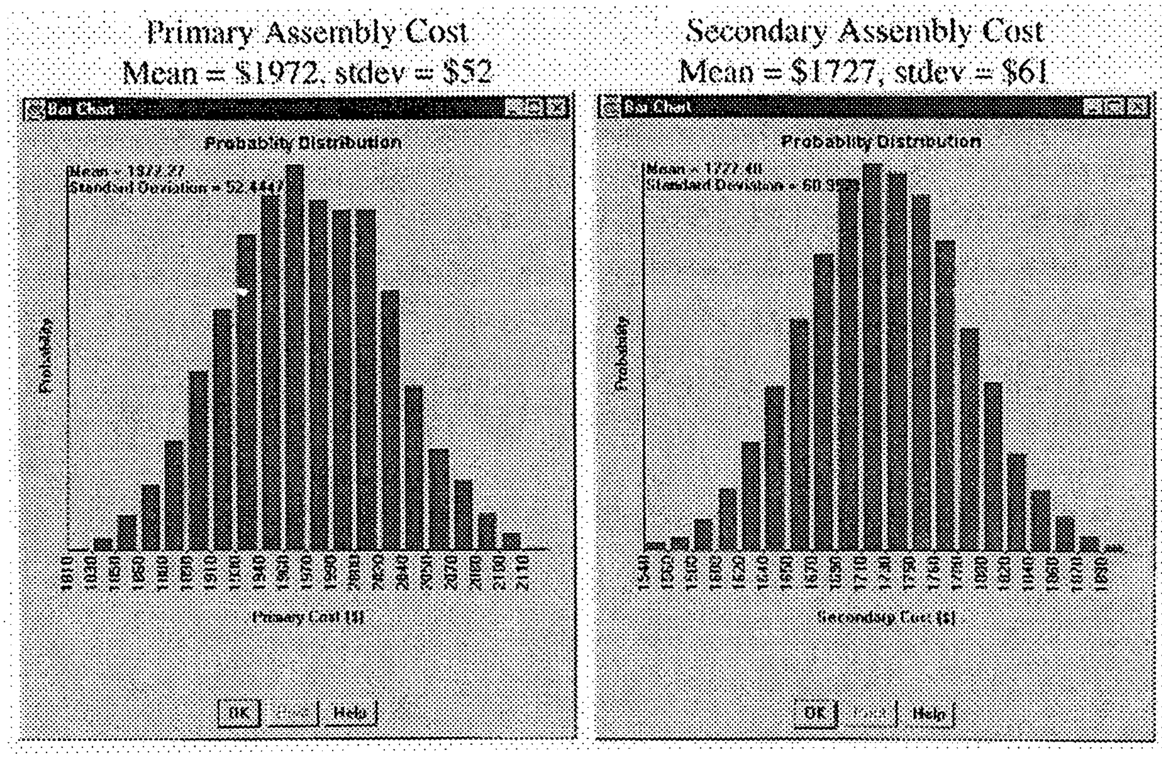


Fig. 7. Cost distributions for building a FPD from salvaged parts drops from $1972 to $1727, given the assumptions stated within the text. The distributions shown are for the 99% confidence level (3 σ).

TABLE V
COMPARISON OF DIFFERENT SALVAGE OPTIONS (MEAN AND STANDARD DEVIATIONS INCLUDED FOR EACH ENTRY)

Salvage Options	Secondary Cost ($)	Secondary Quality	Secondary Waste (g)	Secondary Material Consumed (g)
Salvage all components	$1,727 $62	99.93% 0.03%	2,170 205	1,090 23
Salvage Electrical and Glass only (no Mechanical)	$1,743 $62	99.93% 0.03%	2,514 206	3,090 63
Salvage Electrical only	$1,786 $60	99.94% 0.03%	3,162 219	7,438 187
Salvage LCD Glass Assy, Column and Row Drivers only	$1,945 $59	99.95% 0.02%	10,822 556	8,814 189

than the cost to build the original). Fig. 8b shows results if primary and secondary assembly repurchase is mandatory (i.e., a legislated take back situation). In this case, we use the same analysis as shown in Fig. 8(a), but, the primary assembly repurchase cost is combined with the primary assembly, not with the secondary assembly (and an identical repurchase cost is combined with the secondary assembly as they must be taken back too). This figure shows that under forced take back conditions (imposed for both the primary and secondary assemblies), the buy back cost is irrelevant for determining the relative economics of secondary and primary assemblies (i.e., it is always more economical to manufacture secondary assemblies with the assumptions presented).

The results presented above assume that all functional components, as listed in Table II, are salvaged and reused. It is more likely that only the most expensive components (the electronics and/or the display and drivers) would actually be included in a secondary build. A comparison was made between these possible approaches and the results are given in Table V; (the results in Table V assume an equipment lease situation where all primary assemblies are repurchased and no secondary assemblies are repurchased). These outputs support the supposition that it may not be cost effective to reuse the mechanical components (only a slight decrease in secondary cost was realized when the mechanical parts were salvaged). Recycling of these materials might be a better option, which would lessen the impact on the material consumed, which is the only metric to be significantly affected (3.1 kg versus 1.1 kg). Reusing only the electronics appears to be the next most cost-effective approach, but unless the display and backlight assemblies are recycled there is a large

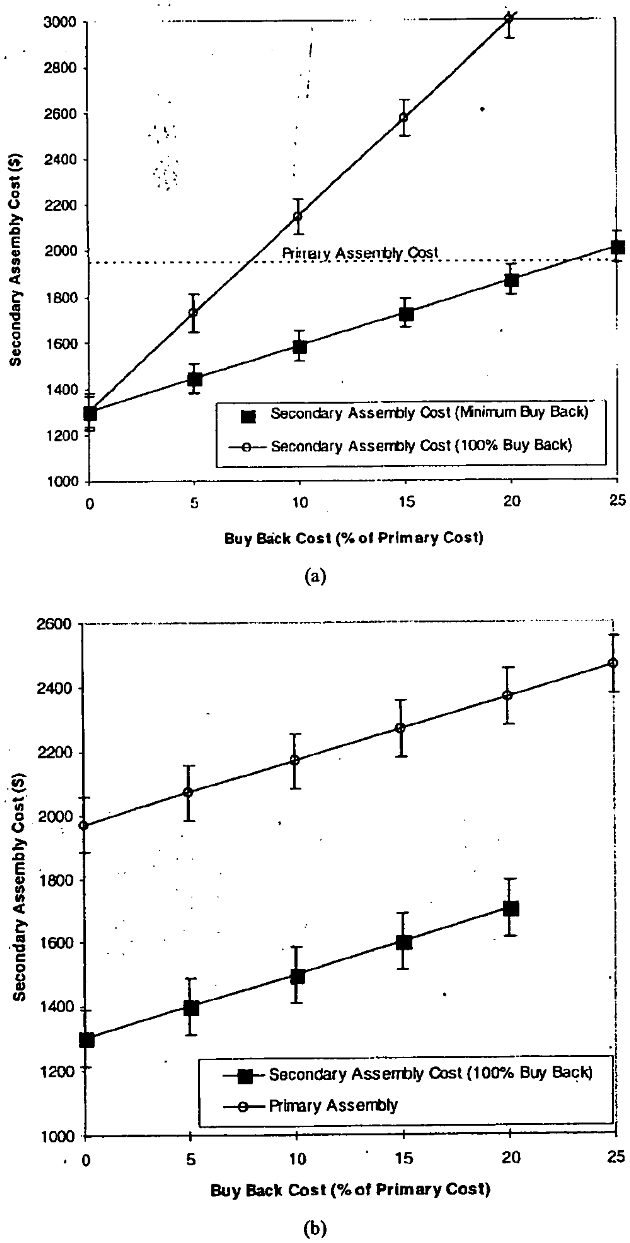


Fig. 8. Secondary assembly cost of the FPD versus the primary assembly buy back cost. Error bars represent 1 σ. (a) primary assembly repurchase is optional, (b) primary and secondary assembly repurchase is mandatory.

negative impact in the amount of materials consumed (7.4 kg). A final decision on the best strategy requires a more detailed analysis, but this high level assessment highlights the areas of concern and indicates where more detailed data and process information are required.

IV. Conclusion

The approach presented in this paper is not intended to be as accurate as a full and detailed life-cycle assessment and should not be interpreted as a replacement for such. However, it does demonstrate the "80/20 rule," which says that 80% accuracy can be obtained with 20% of the effort and data. It is also a means of introducing nonenvironmental experts, such as those in the design and business community, to the inclusion of environmental merit into their decision making process. This methodology can be used to make high-level decisions and illustrates the point that a full life-cycle assessment is not necessarily needed for every product, nor does the product need to be defined in final detail.

Cost is typically one of the best known or most easily estimated metrics. Unfortunately it is often not included in life-cycle assessments or DFE. Any uncertainty in the data inputs and corresponding error in the estimation can be captured by using Monte Carlo simulation. As seen in the example of the primary and secondary flat panel display builds, even with a 10% error for all inputs, the final error (at 2 σ or 95% confidence) is only \$105 out of \$1973 or 5% for the primary build and \$124 out of \$1727 or 7% for the secondary build. This metric is absolutely critical in the implementation of DFE into the business environment. As pointed out in [15], Monte Carlo analysis is not intended to model partial information or higher-order uncertainty, and therefore, does not take the place of critical model inputs that may not be known. However, the use of Monte Carlo analysis allows the analyst to bracket and understand the error and potential risk associated with not having detailed data.

Minimum quality of incoming parts is typically specified by the supplier and maximum quality is theoretically always 100%. In order to use a triangular distribution and Monte Carlo simulation to account for error, the user needs only to estimate the most likely value for the quality of an incoming component or material. The quality of a process step must be calculated by combining the amount of production scrap for each component with the number of field failures. These two quantities can then be used to estimate test effectiveness. In the present analysis, test effectiveness is entered in order to predict scrap and field failures. The quality metric is expected to be most useful when making comparisons and tradeoffs, as in the assembly example. In these cases, relative values are often as valuable as absolute values for decision making.

If sales of the product occur over a significant period of time (i.e., many months or years), then "time value of money" may be a relevant contributor to life cycle costs in tradeoff analyzes that consider product take back. Consider the following simple example: an OEM must either purchase all the parts to satisfy the entire production run for a product up-front before production begins, or gradually over time during production. In the up-front purchase case, the real cost to the OEM of the parts is the amount paid for the parts plus the "opportunity cost" associated with the up-front payment, i.e., the money to make the up-front payment was either borrowed at some interest rate and can not be repaid until the products are sold, or equivalently, the money for the up-front payment is wrapped up in products yet to be sold instead of in the bank earning interest. Whether interest is paid or interest is lost, the opportunity cost must be considered when computing the life cycle cost of the product. In the second case, the OEM may have to contend with inflation that increases the part cost over time. In both cases, remanufacturing leads to additional potential savings because it requires the purchase of a smaller

inventory of parts, thus tying up less money in unsold products and/or creating less exposure to inflation effects. To properly treat the time value of money, a production/inventory model (e.g., [10] or [11]) that includes production volumes, and detailed time lines for primary and secondary manufacturing and product is necessary. This is an analysis which is outside the scope of the model presented here.

Waste is typically the least characterized of the metrics presented in the model. For the purpose of demonstrating the methodology, all waste was lumped together. In an actual product design, it would be desirable to categorize the different types of waste, such as by disposal method. The amount of waste generated per product may often be inaccurate and potentially underestimated because it is common to combine waste for the entire facility. The analysis in this paper made high level assumptions about the amount of waste produced in manufacturing components of certain types. Development of more detailed data modules and/or predictive modules for electronic components will be critical for correctly accounting for this metric.

Material use is of most interest when the inventory results are incorporated into an impact analysis. In this paper, the material use metric was kept very simple. As in the case of waste, more module and model development for electronic products is needed. However, as in the case of waste, there may be many high level decisions that can be made by simply tracking a small number of materials of interest or concern.

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V2/

Assembly/Disassembly Optimization Model (The "Salvage" Model)

[Description] | [Inputs] | [Outputs] | [Features] | [Software] | [Known Bugs] | [Walkthrough] | [References]

Description

A methodology that incorporates simultaneous consideration of economic and environmental merit during the virtual prototyping phase of electronic product design has been developed. The model allows optimization of a product lifecycle that includes primary assembly, disassembly, and secondary assembly using a mix of new and salvaged components. Optimizing this particular lifecycle scenario is important for products that are leased to customers or subject to product takeback laws. Monte Carlo simulation is used to account for uncertainty in the data, and demonstrates that high-level design and process decisions may be made with a few basic metrics and without highly specific data sets for every material and component used in a product. A web-based software tool called "Salvage" has been developed that implements this methodology.

The Salvage tool allows the exploration of the primary assembly, disassembly and secondary reassembly of new systems using selected parts from the disassembled primary unit. The basis for the exploration is cost, quality (yield), waste material, and consumed material. The model computes the characteristics of the primary assembly and testing operation (cost, yield, waste, material consumption), the cost of system disassembly, and the characteristics of assembly and testing of a secondary assembly that uses a combination of new and salvaged parts.

Inputs

Three types of inputs are supported by this application:

1) Component/Material Acquisition – descriptions of all the components used to create the primary and secondary assemblies of the product under design. Examples include: chips, connectors, heat sinks, and printed wiring boards. The following characteristics can be input:

- Primary component cost, quality (yield), waste material generated when the component was originally fabrication, and material consumed when the component was originally fabricated (per component)
- Cost of disassembly (per component)
- Quality after buy back (per component)
- Damage during disassembly (per component)
- Test cost and test effectiveness (per component)
- Whether or not the component is salvaged for the secondary assembly

2) Manufacturing/Assembly – the process of assembling the system (the same process is assumed for both the primary and secondary assemblies). The following characteristics can be input:

- Description of the component mix for each process step

- Attach cost, defects introduced, material wasted, material consumed (Assembly Steps)
- Test cost and test effectiveness (Test Steps)

3) Disassembly/Salvage – special characteristics of the disassembly and take back process. The disassembly process can be custom created by the user or defaulted to the reverse of the assembly process. The following characteristics can be input:

- Fraction of primary parts that are returned and are salvageable
- Ratio of secondary build quantity to primary build quantity
- Buy back cost

Outputs

The following outputs are available for the product under design:

- Primary assembly cost, quality (yield), waste material, material consumed
- Disassembly cost
- Secondary assembly cost, quality (yield), waste material, material consumed
- Bar charts showing the probability distributions associated with any of the above outputs

Features

Special features associated with this application include:

- Option to characterize all input values as distributions (uniform, normal, triangular, lognormal)
- Monte Carlo analysis control
- Editors for process and components
- Full set of help pages

Software

The "Salvage" software is written entirely in Java and is designed to operate as either an application or as a web delivered applet with all calculations are performed on the client computer. A limited number of Beta copies of the software are presently supported. Persons interested in obtaining a Beta version are welcome to email Peter Sandborn at the University of Maryland, however, new Beta site support is limited by current funding.

Known Software Bugs

The following bugs are known to exist in the present version.

1. Use the right mouse button when clicking on the tabs to change forms (the left mouse button is unreliable).
2. Always add or remove rows from tables before you make changes to the data in the cells. Changing forms will lock in all data changes.
3. The units on the mean and standard deviations printed on the bar charts are MKS ($, fraction, kg).
4. The "Confidence level" input on the Setup dialog box is not used at this time.
5. The scatter plots are not completely operational at this time.

6. The tables columns may become jumbled when scrolled horizontally. Changing forms will properly refresh the table.

Walkthrough

A walkthrough presentation containing screen dumps from this application can be viewed: View walkthrough

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Research Horizons
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RAPID PROTOTYPING AND MANUFACTURING

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Rapid Prototyping

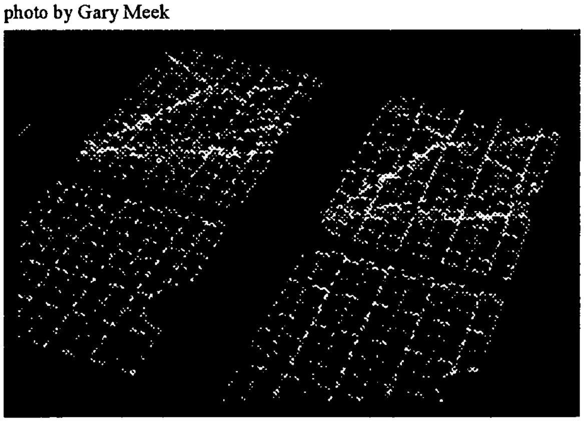
Key to Speedy Manufacturing

By Lea McLees

SPEED AND ACCURACY are the hallmarks of successful, profitable manufacturing in the 1990s. Products that miss target market dates or bear unanticipated design flaws can cost manufacturers dearly in lost sales and development investments, giving competitors an advantage.

And the window for meeting target market dates is shrinking, notes principal research scientist Tom Starr.

photo by Gary Meek



An ultraviolet laser cures a syrupy eposy liquid into a solid prototype inside a stereolithography machine.
(200-dpi JPEG version - 276k)

"Today, products can miss their markets if they are even six months late," says Starr, a researcher in Georgia Tech's School of Materials Science and Engineering.

Leon McGinnis, professor of industrial and systems engineering, agrees.

"Companies today can't afford to make mistakes when they are bringing products to market," he says.

Rapid prototyping and manufacturing (RPM) technologies hold vast potential for ensuring quickly designed, precise products. These methods allow prototypes

-- and perhaps one day, the products themselves -- to be built quickly from computer-aided design (CAD) files using photochemically sensitive resins or other materials. Rapid prototypes are ready within hours or days of design; conventional prototypes can require weeks or months to build or mold.

RPM offers monetary savings, as well. Pratt and Whitney's Rapid Prototyping and Casting Laboratory in Connecticut reported in 1995 having made 2,000 RP castings at a cost of $600,000 to $700,000 -- a savings of $6.4 million, when compared to the $7 million that would have been spent using conventional prototyping methods.

But the availability of RPM technology doesn't guarantee its productive use. Education and experience are necessary, and, as with any technology, RPM could be enhanced with further research and development.

A Project for Students and Industry

To that end, Georgia Tech has formed the Rapid Prototyping and Manufacturing Institute (RPMI) to educate students, address industry RPM needs and shed light on future research directions.

photo by Gary Meek

Georgia Tech mechanical engineering graduate Marcial Machado displays molds used to produce plastic, ceramic or metal parts.
(200-dpi JPEG version - 224k)

Working together to make RPM potentials reality are a dozen educators and researchers in mechanical engineering, materials science and engineering, chemical engineering, industrial design, management and aerospace industrial and systems engineering; representatives of eight companies interested in RPM; and 14 graduate students, says Tom Graver, RPMI director of operations.

"Industry has a clear need to learn how to apply these technologies and how to develop more challenging applications," Graver says. "By primarily focusing on education, we can address the needs of industry while creating outstanding opportunities for our students and faculty."

Member companies include Coca-Cola, Durden Enterprises, Eastman Kodak, Lucent Technologies, Motorola, Siemens, Procter & Gamble and 3D Systems.

"The idea of having a relationship with the RPMI allows us to take advantage of and participate in research and projects to press the edge of the envelope that we normally would not be able to do ourselves," says Allen Brand of Motorola Energy Products.

RPMI began almost three years ago as part of a $1 million Technology Reinvestment Program grant from the Defense Advanced Research Projects Agency. Since then, member

companies have each contributed $25,000 a year to support the educational mission of the RPMI, while researchers have brought in $500,000 in National Science Foundation monies, says McGinnis, one of the writers of the initial grant.

"Industry's immediate need is to be focused on understanding the technology and how to deploy it," McGinnis explains. "The interesting thing is that what comes out of our solving industry's technical problems is a research agenda. Educational activities that involve solving problems often lead to research."

RPMI researchers, member companies and students are working with three technologies, says Reginald Ponder, RPMI lab manager.

- **Stereolithography:** The first rapid prototyping technology introduced commercially, stereolithography (SL) appeared in 1987. It employs an ultraviolet laser that follows a computerized CAD file. As the laser shines through a syrupy liquid resin, it solidifies portions of the liquid into hard, thin, stacked layers, building a 3-D copy of the object modeled in the CAD file.

- **Fused Deposition Modeling:** Fused deposition modeling (FDM) relies on a thermoplastic filament protruding from a heated extrusion head approximately .0012 inches in diameter. A copy of the object in a CAD file is built as the filament melts, forming layers of thermoplastics below the extrusion head.

- **Jet-Modeling:** These machines are three-dimensional ink jet printers. They are used to quickly build inexpensive concept models.

Read on to learn more about RPMI's achievements and goals for these technologies.

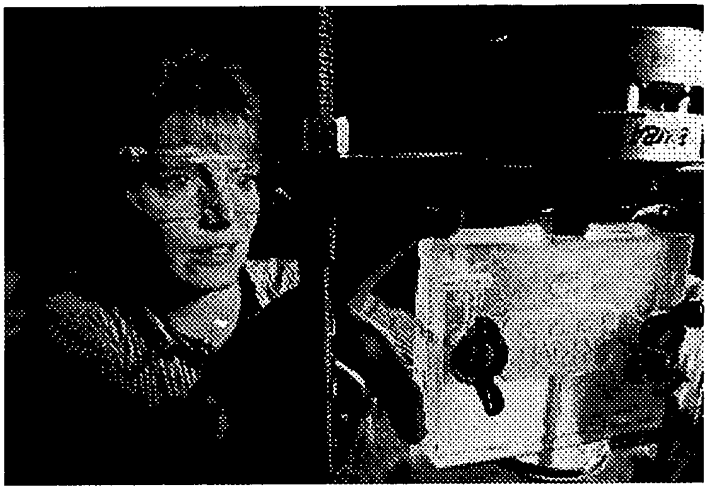
Rapid Prototyping for Ceramics

Combining rapid prototyping and powder injection molding technologies could enhance ceramics use in manufacturing by reducing the amount of time and money needed to use them.

One challenge remains: compensating for the shrinkage involved in powder processing.

photo by Gary Meek

Ceramic parts created with powder molding shrink 10 to 20 percent during firing as the powder particles merge together at high temperatures to form the dense ceramic. This change from the as-molded size can affect the accuracy of the final product. Principal research scientist Tom Starr and Ph.D. student Beth Judson are developing a model that would predict the dimensions



Ph.D. student Beth Judson watches her rapidly made mold fill with aluminum oxide powder.

of the final, fired part within 0.5 percent of the intended size. That would allow designers to create molds that compensate for shrinkage.

"We're using finite element analysis," Judson says. "Right now we're working with aluminum oxide. It's the workhorse of the ceramic industry -- most technical ceramic parts are made of it."

If shape is a controlling factor, finite element analysis would be done with each shape. If material flow is a controlling factor, equations could be developed for different types of materials and process conditions.

Industries that might benefit from this research include textiles, where ceramic thread guides are used; and areas such as aerospace, automotive manufacturing or soft drink production that use nozzles, air foils, rotors or other such parts for high-temperature or potentially corrosive applications.

The work Judson and Starr are doing might be especially useful in short-term manufacturing, Starr notes.

"For example, if you wanted 100 parts out of stainless steel for a military aircraft that isn't made anymore, do you invest in a metal mold for $30,000, or do you do it this way?" Starr noted. "You can't amortize that cost over just a few parts. And the process we're working with would work for metal, as well as ceramic, parts."

Georgia Tech is pursuing a patent on the shrinkage prediction model.

Estimating Prototype Build Time

Once a CAD design is sent to a stereolithography machine for building, the user knows the part will be completed -- but not how long it will take.

"It is difficult to estimate build time because it is dependent on so many variables, such as part size, layer thickness, laser power, resin and other factors," says Joel McClurkin, a graduate student who completed his master's degree in mechanical engineering in June.

photo by Gary Meek

Notes his adviser, Dr. David Rosen: "The [rapid prototyping] machine must perform thousands or millions of small operations to make a part. Until now, no one has added up the times for all these operations."

RPM has potential applications in preparing for medical procedures and re-creating damaged bone structure, says lab manager Reginald Ponder.

Enter the build-time estimator. Developed by McClurkin working with Rosen, the program estimates how long a 3D Systems SLA (stereolithography apparatus) will need to build a part by analyzing the CAD file of the prototype in question.

"The build time estimator reads the vector and range files and makes an estimate based on the information in those files," McClurkin explained. "The vector and range files contain the 'low level' information that actually controls the operation of the SLA. The biggest task here was cracking the vector file to determine the location of the information I was looking for."

The program (available at http://rpmi.marc.gatech.edu/BTE.html) needs only three pieces of information: the name of the resin being used, the resin's penetration depth or critical exposure; the power at which the laser will be operating; and the name of the range and vector files of the drawing for which the user wants a build time estimate.

McClurkin made dozens of comparisons of estimates with the true build time for a variety of parts and gathered feedback from industry users, finding an average error of 2 to 3 percent.

The build time estimator is part of a software package McClurkin completed and demonstrated for his master's thesis. The package will help SL users select from numerous possible SL build styles, taking into account build time, surface finish, accuracy, post processing time and other factors.

Measuring What You've Made

No manufactured part is a perfect match to the CAD file from which it was generated. Defects occur randomly or because of problems associated with the manufacturing process, says Tom Kurfess, an associate professor of mechanical engineering.

His specialty is measuring objects with a coordinate measurement machine (CMM) to determine how to replicate them, or how closely they resemble original CAD files, Kurfess says.

"Once the object is in the CMM, a trigger probe touches the surface of the object in a variety of locations in three dimensions, giving XYZ coordinates off its surface," Kurfess

explains. "The data points are connected with curves, surfaces and solids to represent or measure the object."

Among the issues Kurfess and his students are studying are the best ways to take data points, connect them and fit them to complex surfaces; ensuring a good data fit; and identifying the types of deformation that result during RPM, and their causes. If characteristic types of deformation are found to be associated with certain types of RPM, they might be eliminated in the future by modifying the CAD file involved.

"We have a lot of support from industry and government to address these issues," Kurfess said. "Our work extends beyond the rapid prototyping issues. Our target is extremely complicated geometry -- and we know exactly how to look at it."

Small, Speedy Product Runs

RPM is extremely useful for creating tooling used in short manufacturing runs, says Dr. David Rosen, assistant professor of mechanical engineering.

"We're looking for good ways to develop tools to produce a small quantity of plastic parts in end-use material, using manufacturing equipment like injection molds," says Rosen, who also serves as RPMI academic director.

Currently, injection molds can take several weeks or months to produce. Rosen's goal is to go from CAD model to molded parts in four days -- he thinks that will be possible within the next three years.

One aspect of this work involves fine-tuning the production of injection molds using SL machines, and speeding up that process. An approach that Rosen and his students are looking at is building shells and filling them with epoxy or metal.

"Rather than building a solid mold on the SLA machine, which takes about 35 hours, we build the shell of the mold in about 15 hours and at one-tenth the cost," Rosen says.

Beyond Rapid Prototyping

Key Focus Areas for the Rapid Prototyping and Manufacturing Institute

- Making tooling rapidly: Harnessing emerging rapid tooling methods to develop processes that quickly, inexpensively produce five to 500 parts in end-use materials.
- Modeling and predicting form errors in rapid prototyping parts: Understanding errors in RPM processes so that parts more closely match design specifications.
- Rapid manufacturing of composites: Developing faster methods for building large, complex composite structures.
- Refining, validating and handling data: Making production of a prototype part from a solid CAD model easier.
- Developing functional prototypes: Making working prototypes that snap together, move as an assembly and

Prototype development and use is part of a larger, holistic picture being explored by Rosen and Dr. Farrokh Mistree, professor of mechanical engineering. They are exploring the application of the best type of prototype -- physical or computer -- in different situations.

"Depending on the information we want to gain from the model, we don't necessarily need a product- representative prototype," Rosen says. "In some cases, we may not need physical prototypes -- virtual, computerized prototypes tend to be even more rapid."

They also are looking beyond product manufacturing to other needs that should be considered during design -- service and disassembly.

"At the end of a product's life there are a couple of different strategies," explains Mistree, who also works in Georgia Tech's Systems Realization Lab.

"One is to throw whatever you have into the waste basket. Another approach is to disassemble it and take out valuable components. Or, you could recycle the materials. How do you assess product assembly and disassembly characteristics? One way is to build a physical prototype and study it."

look like a finished product.

- Finding alternate materials: Determining which are best and which meet specific needs.

- Investigating the role of prototyping in product design: Exploring how companies should use rapid prototyping resources in developing new products.

- Optimizing rapid prototyping build parameters: Improving understanding of rapid prototyping processes so users know which variables to manipulate to achieve desired build speed, part accuracy, surface finish and prototype cost.

RPMI hosts a yearly symposium focusing on RPM applications. Over its first three years, the Gwaltney Manufacturing Symposium attained a reputation for being one of the premiere events of its kind in the world. This year's meeting is scheduled Sept. 30-Oct. 2. For more information, see RPMI's Web site at http://rpmi.marc.gatech.edu/.

RPM will greatly contribute to development of principles for disassembly, a companion to the principles for assembly developed 15 years ago, he notes.

"Because we have rapid prototyping and virtual prototyping abilities, we should be able to come up with principles for disassembly much more quickly," he says.

Future RPM Research at Tech

What does the future hold for rapid prototyping and manufacturing technology? It could evolve into rapid manufacturing, predicts Steven Danyluk, director of Georgia Tech's Manufacturing Research Center (MARC). RPMI is one of the main focuses in MARC's work toward enhancing manufacturing education and research.

"If you needed to make a specific honeycomb product, you could make it out of a polymer, and further fabricate and use it in a production environment," he says.

Further materials research could make that prediction reality, says Bob Schwerzel, principal research scientist in the Georgia Tech Research Institute's Electro-Optics, Environment and Materials Laboratory.

"We'd like to develop new polymers and resins with new properties that would allow RPM to be used as a general manufacturing tool, and not just as prototyping tool," he notes. "I think controlling the material properties of the resin in the biggest challenge."

And eventually, RPM may contribute to the increased use of flexible systems in manufacturing that adapt quickly to changing market needs, Rosen notes.

"You really need your manufacturing equipment and tools to be modular and adaptable, and that's quite difficult to do -- so it remains to be seen how well rapid prototyping technologies can help us do mass customization and product variety," he says.

Further information on RPMI is available from Tom Graver, Rapid Prototyping and Manufacturing Institute, Georgia Institute of Technology, Atlanta, GA 30332-0406. (Telephone: 404/894-5676) (E-mail: tom.graver@marc.gatech.edu)

Check out RPMI's web site at: http://rpmi.marc.gatech.edu/.
